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BRUSHLESS ROTATING ELECTRICAL GENERATORS FOR SPACE AUXILIARY POWER SYSTEMS

(NASA CONTRACT NO. NAS3-2783)

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

by

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ABSTRACT

This report contains a design calculation procedure and a Fortran II computer program for synchronous, wound-pole, salient-pole generators.

In addition, it contains the design calculation procedure for Lundell generators.

Losses in solid pole faces and the design limits imposed by them are discussed.

Lundell generators have limits of stator length to rotor diameter that cannot be profitably exceeded. These are discussed.

A brief discussion of the motor starting characteristics of salient pole generators is included.

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INTRODUCTION AND SUMMARY

Introduction

This report is submitted by The Power Equipment Division of Lear Siegler Corporation as the second part of a study of brushless rotating electrical generators. The work was accomplished during the period October 26 to January 26.

Summary

Purpose and Objectives

The objective of this study is a report that will help to select the proper brushless generator for a specific application and provide a computer program to calculate the performance of the selected generator design.

To provide a basis for properly evaluating the different generator types, design calculation procedures and computer programs are being provided for those that appear most suitable. From these programs parametric curves of output vs. size, weight and speed as well as efficiency can be readily obtained.

The final reports will be two topical reports:

1. General Selection Criteria and Mechanical Analysis of all Generator Types Studied.

2. Electrical Calculations and Evaluation of all generator types studied.

In the first quarterly report, a statement was made to the effect that each succeeding report would contain all material contained in preceding reports. This has been changed and now only the final reports will contain all of the previously published reports. When Bell programs are rewritten in Fortran, only the Fortran programs will be included in the final report.

WOUND-POLE, SALIENT-POLE GENERATOR

THE WOUND-POLE, SALIENT-POLE, A. C. GENERATOR

The salient-pole, synchronous generator with wound poles is the standard generator of the electrical industry. It has the highest electrical power output per pound per rpm of any practical electrical generator presently known. Because of its wide spread use and its superiority, all other types of electrical generators are compared to the wound-pole, salient-pole synchronous generator.

It is used on both aircraft and utility systems almost to the exclusion of any other types except non-salient pole, wound rotor, generators (or turbine generators) which are used with 1800 rpm and 3600 rpm steam turbines in central station generating plants.

In addition to its use as an electrical generator, the salient-pole, wound-pole, machine makes the best synchronous motor known. The pole heads can be designed with cage windings so that the machine can start a substantial load as an induction motor. The cage windings can be made double to give good starting characteristics and good pull-in characteristics.

Within its usable range, the wound-pole synchronous generator has no equal, but its range of usefulness is limited. Its maximum rotor peripheral speed is low because of the field windings supported by the poles and the high stresses resulting from the centrifugal loads. Its output frequency is low because the possible number of poles is restricted by electrical and mechanical limits due to the field windings, pole construction and the need for having at least one slot/phase/pole in the stator. Its maximum operating temperature is about 600° F for the copper and insulation on the rotor and 350° F for the rotating (silicon) rectifiers.

These thermal limits, plus the silicon rectifiers' susceptibility to radiation damage, have forced the need for other more rugged types of generators all of which are heavier, on a KVA/revolution basis, than the old standby wound-pole, salient-pole machine.

It is well to remember that within its application range, no other type of a-c generator can compare with the wound-pole, salient-pole machine and it should be used whenever feasible.

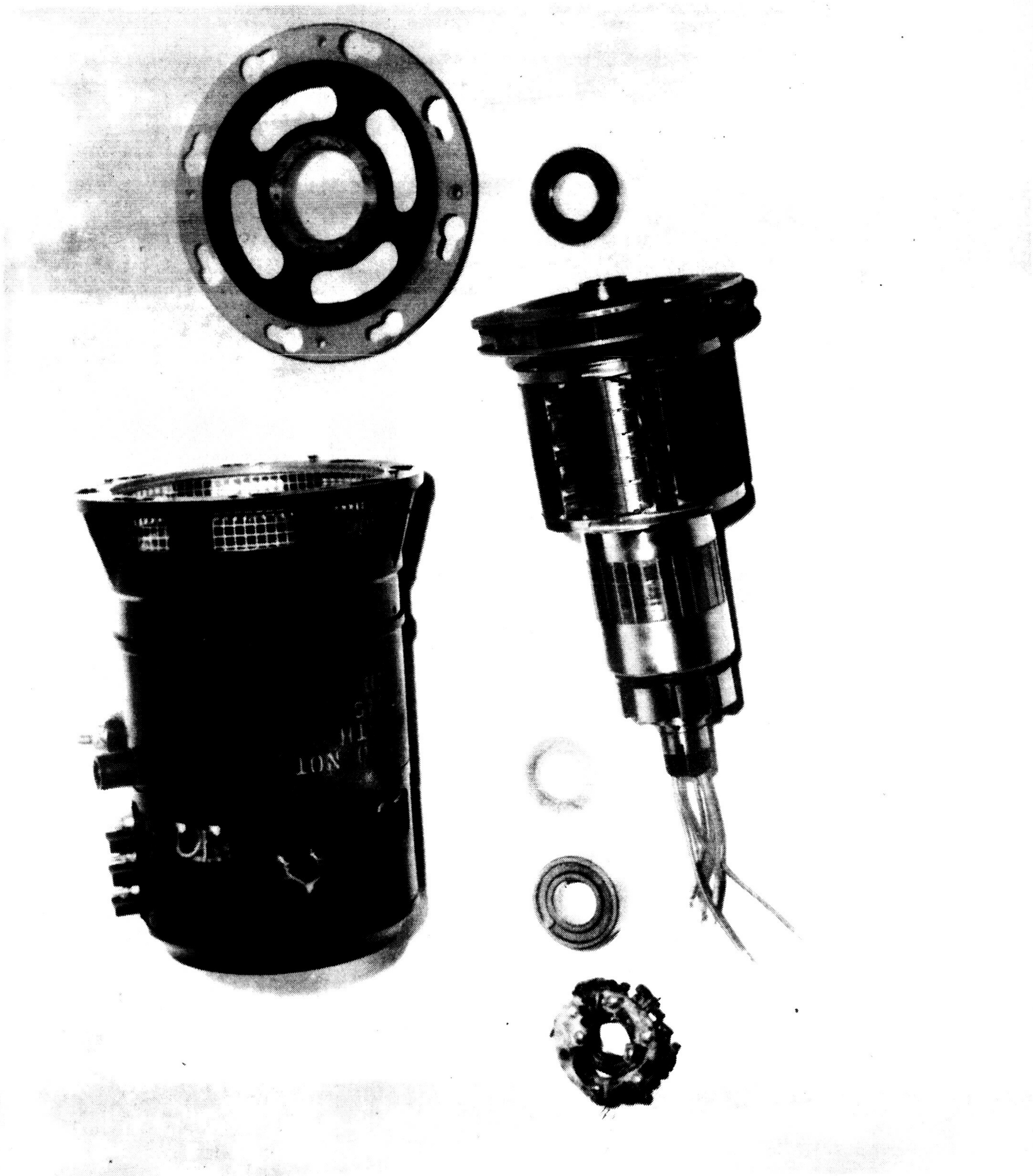


Photo # 6 ROTATING RECTIFIER GEN.

The Wound Pole, Salient Pole A.C. Generator section of the First Quarterly Report has been reassembled and rewritten for this Second Quarterly Report. The design manual and equations are now presented as one document. The computer program has been rewritten in the Fortran computer language using the fixed decimal system on the input and output sheets. The complete package is called "The Salient Pole Computer Design Manual".

This Computer Design Manual in its entirety contains the following:

1. A numbered series of definitions and equations forming the body of the design calculations.
2. A list of numbered symbols.
3. A collection of tables, graphs and figures that are necessary in preparing an input sheet.
4. Standard magnetization curves.
5. An input and output computer design sheet.
6. A complete list of Fortran symbols.
7. A complete list of Fortran equations.

Design Procedure

This computer program is an analysis procedure. In an analysis procedure, all of the machine dimensions and winding specifications are given in addition to the rating. With all of this information given, the computer calculates the performance of the machine.

A generator design starts with the input sheet. All of the information that has been gathered on the generator in question is recorded on the input sheet. The inputs listed on the input sheet follow the sequence of the design manual calculations sequentially except for a few isolated cases. Each input is identified in three ways: (1) by a symbol, (2) by an explanation of each symbol, and (3) by an identification number which is bracketed in parenthesis. This identification number or item number shows the location of the particular input in the design manual. At each location in the design manual, a complete explanation is given for each symbol in question along with equations where they apply.

For example, given on the input sheet is (4) E_{PH} phase volts. If there is any question by the designers as to just what is meant by phase volts or how is it calculated, he need only to look up item (4) in the design manual. Item (4) gives the following explanation:

For three phase delta connected generators

$$E_{PH} = \frac{(\text{Line Volts})}{\sqrt{3}} = \frac{(3)}{\sqrt{3}}$$

For three phase wye connected generators

$$E_{PH} = (\text{Line Volts}) = (3)$$

Each item, as shown in Item 4 above, has 3 parts:

1. A word definition explaining the item,
2. An equation using symbols,
3. An equation using the location for each symbol
   a. When a number in an equation is bracketed by parenthesis such as (3) in Item 4, it has no numerical value. It represents the location of the symbol that is used in the equivalent equation
   b. When a number such as $\sqrt{3}$ in Item 4 is not bracketed by parenthesis, then it is a real number and must be used accordingly.

A few of the items on the input sheet can be either an input or an output. This is useful where the designer wants better control of the design. By inserting an adjusted number as an input, it may be possible for the designer to simulate an actual known condition rather than accept the standard calculated answer.

When the designer is satisfied that the existing or standard calculation satisfies his condition, then he need only to insert a zero (0), and the computer will do the calculating.

A minimum number of rules must be followed in order to make a computer design -

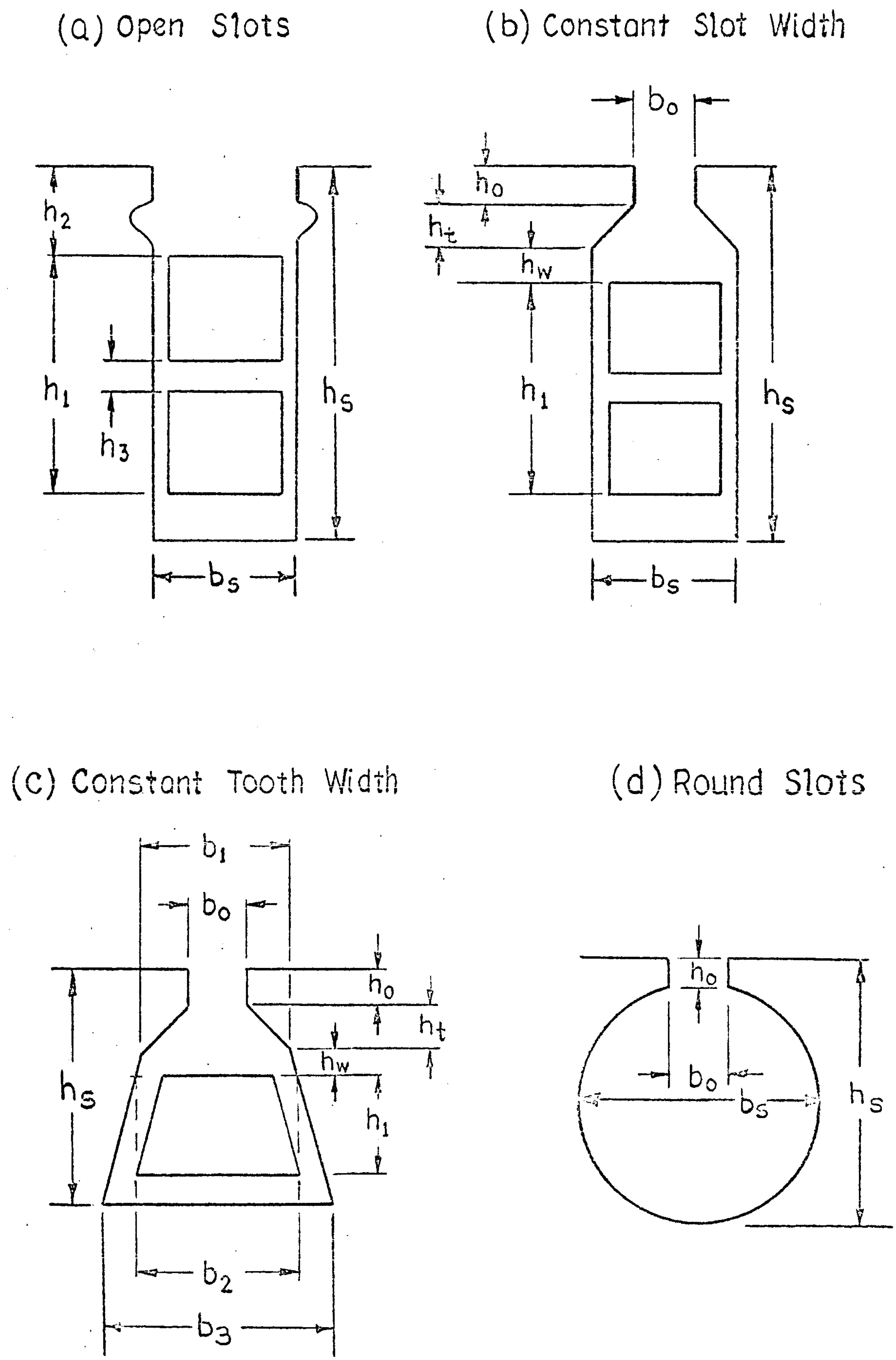
1. Fill out input sheet completely.
2. All whole numbers and zeros must be followed by a decimal point. For example, if the number that is to be used on the input is either 1, 2, or 0, they must be inserted as 1., 2., or 0. . All decimal numbers are accepted as is. That is, 1.4 should be entered as 1.4.
3. When a question arises about a particular input, refer back to the location per the item number for a detailed explanation.
4. When a particular magnetization curve is to be used, the proper code number should be used as an input if the curve is available on "card decks". The code number can be any number that is mutually agreed on by the designers and the computer operators. The code simply tells the operator which curve to use.

   When the curve does not exist on a "card deck", then the designer must submit on a separate sheet of paper, 29 points from the curve that is to be used. These points are the ampere turns per inch for each 5 units on the density scale, where the density scale is in Kilolines per in^2. Start the first reading at 0 density.

Output Sheet

The output sheet is set up for the computer to type out the answers directly in the spaces provided. The space is set up to accept 5 places to the left and right of the decimal point. Single spacing is used on the vertical and regular type spacing on the horizontal

Each item on the output sheet can be checked out by referring back to the item number in the design manual in the same manner as outlined above for the input data.



(a) Open Slots
h2
h1
h3
hs
bs
(b) Constant Slot Width
bo
ho
ht
hw
h1
hs
bs
(c) Constant Tooth Width
b1
bo
ho
ht
hw
hs
h1
b2
b3
(d) Round Slots
ho
bo
bs
hs

FIG 1

TABLE - 1

CHORD FACTORS K_p FOR HARMONICS … DIFFERENT PITCHES

q_1														y/mq																									
1	3/3																																2/3						
2	6/6																																4/6						
3	9/9											8/9										7/9											6/9						
4	12/12								11/12																9/12								8/12						7/12
5	15/15						14/15							13/15						12/15							11/15						10/15				9/15		
6	18/18					17/18						16/18					15/18					14/18						13/18					12/18						
7	21/21				20/21					19/21					18/21				17/21					16/21					15/21				14/21						
8	24/24			23/24					22/24				21/24				20/24				19/24				18/24					17/24			16/24			15/24			14/24
9	27/27		26/27					25/27				24/27				23/27		22/27				21/27				20/27					19/27		18/27		17/27			16/27	
10	30/30	29/30					28/30				27/30			26/30			25/30			24/30			23/30				22/30					21/30	20/30	19/30			18/30		
s/m	1.0	967	964	959	952	945	934	926	917	905	906	[illegible]	875	867	857	852	833	815	810	800	792	779	767	762	750	741	734	722	712	709	705	700	667	634	630	625	600	574	564
1	1.0	999	973	978	977	996	995	993	991	987	988	985	931	979	975	973	966	953	956	951	947	940	934	931	924	918	914	906	901	897	894	891	866	339	835	831	809	800	793
3	1.0	983	985	981	975	966	951	940	924	901	891	865	831	807	782	766	707	643	623	588	556	500	454	434	383	342	309	259	222	195	174	156	0.0	156	174	195	309	342	383
5	1.0	966	959	947	931	906	866	835	773	733	707	643	556	500	423	366	259	116	075	0.0	065	174	259	295	383	447	500	574	623	660	690	707	866	966	974	932	1.0	993	993
7	1.0	943	910	897	866	819	743	696	609	500	454	342	177	105	0.0	052	259	447	500	588	659	766	839	866	924	950	975	976	1.0	998	993	983	866	629	588	559	309	225	139
9	1.0	897	866	831	782	707	588	500	383	223	156	0.0	191	304	434	500	707	866	901	951	981	1.0	998	975	924	866	804	707	623	556	500	454	0.0	358	407	462	500	755	875
11	1.0	834	802	750	680	574	407	287	131	075	156	342	556	660	782	795	966	998	989	951	897	766	629	553	383	231	105	037	222	321	396	454	866	997	994	931	809	721	618
13	1.0	777	727	651	553	423	209	058	131	355	454	643	831	914	975	993	965	802	733	[illegible]	942	174	052	148	333	550	669	810	901	947	975	933	866	371	294	195	309	451	598
15	1.0	707	643	551	454	259	0.0	174	333	621	707	866	981	1.0	975	940	707	342	223	0.0	195	500	707	782	924	981	1.0	966	907	831	766	707	0.0	696	760	831	1.0	982	930
17	1.0	629	550	442	215	037	203	396	601	[illegible]	571	985	921	914	700	600	259	231	365	588	752	940	999	997	924	802	669	423	222	065	053	156	866	940	818	831	309	100	113
19	1.0	545	449	321	141	007	407	597	793	[illegible]	909	985	831	669	438	207	259	727	826	951	999	940	777	330	383	116	105	423	623	752	835	891	866	072	097	194	809	952	989
21	1.0	454	342	195	0.0	259	500	736	920	1.0	988	866	556	309	0.0	174	707	985	1.0	951	831	500	156	0.0	333	643	804	966	1.0	981	940	891	0.0	881	935	981	809	628	402
23	1.0	350	231	[illegible]	149	423	793	[illegible]	991	[illegible]	091	643	195	105	438	597	966	913	826	[illegible]	321	174	545	[illegible]	924	993	773	819	622	442	281	156	866	772	696	555	301	566	778
25	1.0	251	116	[illegible]	275	574	366	900	991	826	707	342	195	500	782	[illegible]	966	550	365	0.0	321	766	966	997	924	721	500	037	222	442	597	707	866	061	383	555	1.0	951	809
27	1.0	170	0.0	195	434	707	951	1.0	924	624	454	0.0	556	809	975	1.0	707	0.0	223	558	831	1.0	897	782	333	0.0	305	707	901	931	1.0	988	0.0	983	1.0	981	309	025	356
29	1.0	052	116	321	563	819	975	973	713	365	156	342	831	978	975	844	259	550	733	951	998	766	358	148	383	727	914	976	901	752	597	454	866	569	412	194	809	965	995
31	1.0	052	231	442	690	906	995	079	109	075	156	643	951	978	782	577	259	915	989	951	752	174	358	533	924	998	914	574	222	065	281	454	866	517	673	831	809	525	162
33	1.0	156	372	556	732	966	951	766	383	223	454	866	981	809	434	174	707	985	901	500	195	500	891	975	924	643	309	259	623	831	945	988	0.0	992	946	831	307	666	910
35	1.0	259	449	659	866	996	866	597	131	500	707	985	831	500	0.0	267	966	727	500	0.0	942	940	966	866	383	116	500	906	1.0	947	835	707	866	294	079	194	1.0	905	637
37	1.0	358	550	750	931	976	743	396	131	793	891	995	556	105	434	696	966	231	075	588	897	940	545	295	333	802	976	906	623	321	053	156	866	855	884	981	309	150	577
39	1.0	454	643	831	975	966	588	174	383	901	988	866	195	309	782	940	707	342	623	951	981	500	156	434	924	985	809	259	222	556	766	891	0.0	909	780	555	805	990	939
41	1.0	545	727	831	997	966	407	059	609	939	983	643	195	669	975	933	259	802	956	951	659	174	777	931	924	550	105	574	901	978	973	891	866	010	264	555	809	414	088
43	1.0	629	802	947	997	819	268	207	793	909	891	342	556	914	975	795	259	998	956	588	065	766	919	931	333	231	669	996	901	660	396	156	866	916	990	981	309	754	984
45	1.0	707	866	937	925	707	0.0	500	924	901	707	0.0	831	1.0	782	500	707	866	623	0.0	556	1.0	707	434	383	866	1.0	707	222	145	500	707	0.0	739	523	194	1.0	844	262
47	1.0	777	910	990	931	574	203	686	991	733	404	342	921	914	[illegible]	058	966	749	075	588	947	766	052	295	924	753	669	087	623	897	993	988	866	312	575	831	305	273	762
49	1.0	839	958	990	866	423	407	835	991	500	156	643	981	669	0.0	396	966	116	500	951	947	174	629	866	224	597	105	819	1.0	897	690	454	866	974	979	831	809	1.0	823
51	1.0	891	985	981	782	259	588	940	924	223	156	866	831	309	434	766	707	643	901	951	556	500	939	975	383	342	809	966	623	195	174	454	0.0	501	203	194	805	297	333
53	1.0	934	[illegible]	947	600	087	743	993	793	075	454	985	556	105	782	973	259	950	989	588	065	940	839	583	333	918	978	427	222	660	[illegible]	[illegible]	866	585	818	981	309	721	997
55	1.0	966	978	877	563	087	866	993	605	365	707	985	195	500	975	973	259	955	733	0.0	659	940	259	143	924	918	500	423	901	978	894	707	866	979	853	555	1.0	771	187
57	1.0	[illegible]	985	831	934	255	951	940	383	624	891	866	195	809	975	766	707	643	223	588	981	500	454	782	924	342	309	966	901	556	174	156	0.0	215	141	555	309	407	899
59	1.0	919	958	756	295	423	995	835	131	826	988	643	556	978	782	396	966	116	365	951	897	174	934	997	383	597	914	819	222	321	[illegible]	891	866	863	965	981	809	994	777
61	1.0	973	973	659	149	574	995	686	131	956	983	342	831	978	[illegible]	058	966	449	826	951	442	766	934	680	383	953	914	087	623	947	993	891	866	972	625	194	809	175	557
63	1.0	988	866	556	0.0	707	051	500	383	1.0	891	0.0	981	809	0.0	509	707	866	1.0	588	195	1.0	454	0.0	924	866	309	707	1.0	831	500	156	0.0	091	468	831	309	894	947
65	1.0	966	802	442	149	814	866	287	609	956	707	342	981	500	434	795	259	978	826	0.0	752	766	259	680	924	231	500	996	623	065	396	707	866	946	997	831	1.0	686	063

TABLE-2

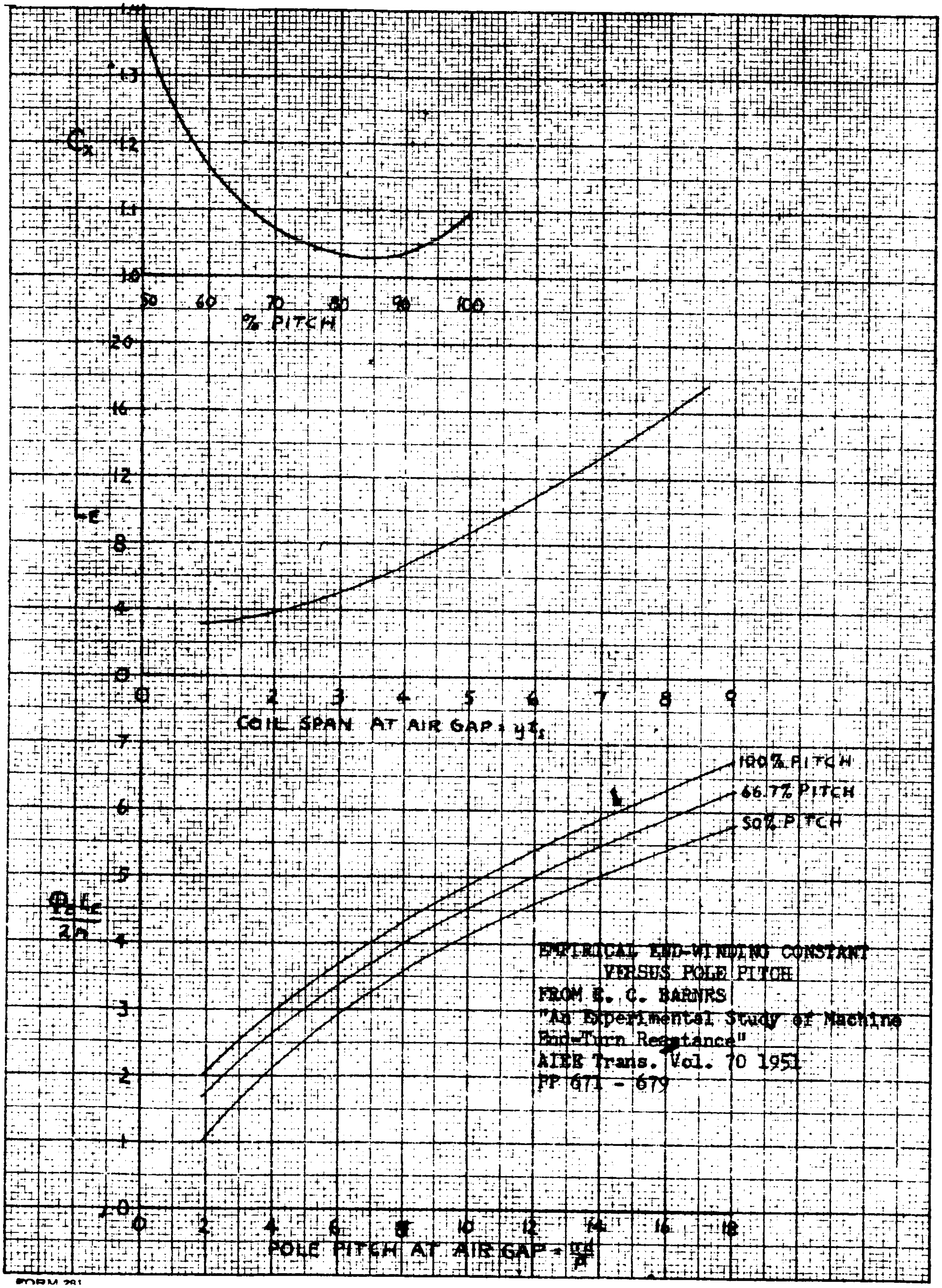
-VALUES OF K_{dn} FOR INTEGRAL SLOT 3ϕ WINDINGS [10]

n	K_{dn} - HARMONIC DISTRIBUTION FACTORS									
$q=$	2	3	4	5	6	7	8	9	10	∞
1	.966	.960	.958	.957	.957	.957	.956	.955	.955	.955
3	.707	.667	.654	.646	.644	.642	.641	.640	.639	.636
5	.259	.217	.205	.200	.197	.195	.194	.194	.193	.191
7	-.259	-.177	-.158	-.149	-.145	-.143	-.141	-.140	-.140	-.136
9	-.707	-.333	-.270	-.247	-.236	-.229	-.225	-.222	-.220	-.212
11	-.966	-.177	-.126	-.110	-.102	-.097	-.095	-.093	-.092	-.087
13	-.966	.217	.126	.102	.092	.086	.083	.081	.079	.073
15	-.707	.667	.270	.200	.172	.158	.150	.145	.141	.127
17	-.259	.960	.158	.102	.084	.075	.070	.066	.064	.056
19	.259	.960	-.205	-.110	-.084	-.072	-.066	-.062	-.060	-.059
21	.707	.667	-.654	-.247	-.172	-.143	-.127	-.118	-.112	-.091
23	.966	.217	-.958	-.149	-.092	-.072	-.063	-.057	-.054	-.041
25	.966	-.177	-.958	.200	.102	.075	.063	.056	.052	.038
27	.707	-.333	-.654	.646	.236	.158	.127	.111	.101	.071
29	.259	-.177	-.205	.957	.145	.086	.066	.056	.050	.033
31	-.259	.217	.158	.957	-.197	-.097	- 070	-.057	-.050	-.031
33	-.709	.667	.270	.646	-.644	-.229	-.150	-.118	-.101	-.058
35	-.966	.960	.126	.200	-.957	-.143	-.083	-.062	-.052	-.027
37	-.966	.960	-.126	-.149	-.957	.195	.095	.066	.054	.026
39	-.707	.667	-.270	-.247	-.644	.642	.225	.145	.112	.049
41	-.259	.217	-.158	-.110	-.197	.957	.141	.081	-.060	.023
43	.259	-.177	.205	.102	.145	.957	-.194	-.093	-.064	-.022
45	.707	-.333	.654	.200	.236	.642	-.641	-.222	-.141	-.042
47	.966	-.177	.958	.102	.102	.195	-.956	-.140	-.079	-.020
49	.966	.217	.958	-.110	-.092	-.143	-.956	.194	.092	.019
51	.707	.667	.654	-.247	-.172	-.229	-.641	.640	.220	.038
53	.259	.960	.205	-.149	-.084	-.097	-.194	.955	.140	.018
55	-.259	.960	-.158	.200	.084	.086	.141	.955	-.193	-.017
57	-.707	.667	-.270	.646	.172	.158	.225	.640	-.639	-.033
59	-.966	.217	-.126	.957	.092	.075	.095	.194	-.955	-.016
61	-.966	-.177	.126	.957	-.102	-.072	-.083	-.140	-.955	.016
63	-.707	-.333	.270	.646	-.236	-.143	-.150	-.222	-.639	.030
65	-.259	-.177	.158	.200	-.145	-.072	-.070	-.093	-.193	.015

TABLE-3
Round Copper Wire

Size AWG	Bare Diameter	Area □"	Ω/1000' @25°C	Single Formvar	Heavy Formvar	Single Glass Formvar	Bare Wt. #/1000'	Single Glass Silicone	Double Glass Silicone
36	.0050	.0000196	424	.0056	.0060		.0757		
35	.0056	.0000246	338	.0062	.0066		.0949		
34	.0063	.0000312	266	.0070	.0074		.1201		
33	.0071	.0000396	210	.0079	.0084		.1526		
32	.0080	.0000503	165	.0088	.0094	.0121	.1937		
31	.0089	.0000622	134	.0097	.0104	.0130	.2398		
30	.0100	.0000785	106	.0108	.0116	.0142	.3025	.0132	.0152
29	.0113	.000100	83.1	.0122	.0130	.0156	.3866	.0145	.0165
28	.0126	.000125	66.4	.0135	.0144	.0169	.4806	.0158	.0178
27	.0142	.000158	52.6	.0152	.0161	.0186	.6101	.0174	.0194
26	.0159	.000199	41.7	.0169	.0179	.0203	.7650	.0191	.0211
25	.0179	.000252	33.0	.0190	.0200	.0224	.970	.0211	.0231
24	.0201	.000317	26.2	.0213	.0223	.0263	1.223	.0251	.0276
23	.0226	.000401	20.7	.0238	.0249	.0289	1.546	.0276	.0301
22	.0254	.000507	16.4	.0266	.0277	.0317	1.937	.0303	.0328
21	.0285	.000638	13.0	.0299	.0310	.0349	2.459	.0335	.0360
20	.0320	.000804	10.3	.0334	.0346	.0384	3.099	.0370	.0395
19	.0360	.00102	8.14	.0374	.0386	.0424	3.900	.0409	.0434
18	.0403	.00126	6.59	.0418	.0431	.0468	4.914	.0453	.0478
17	.0453	.00159	5.22	.0469	.0482	.0519	6.213	.0503	.0528
16	.0508	.00204	4.07	.0524	.0538	.0575	7.812	.0558	.0583
15	.0571	.00255	3.26	.0588	.0602	.0639	9.87	.0621	.0646
14	.0641	.00322	2.58	.0659	.0673	.0710	12.44	.0691	.0716
13	.072	.00407	2.04	.0738	.0753	.0789	15.69	.0770	.0795
12	.0808	.00515	1.61	.0827	.0842	.0877	19.76	.0858	.0883
11	.0907	.00650	1.28	.0927	.0942	.0977	24.90	.0957	.0982
10	.102	.00817	1.02	.1039	.1055	.1089	31.43	.1069	.1094
9	.114	.0102	.814	.1165	.1181	.1225	39.62	.1204	.1254
8	.129	.0131	.634	.1306	.1323	.1366	49.98	.1345	.1395
7	.144	.0163	.510	.1465	.1482	.1525	63.03	.1503	.1553
6	.162	.0206	.403	.1643	.1661	.1703	79.44	.1680	.1730
5	.182	.0260	.319	.1842	.1861	.1902	100.2	.1879	.1929
4	.204	.0327	.254				126.3	.2103	.2153
3	.229	.0412	.202				159.3		
2	.258	.0523	.159				200.9		
0	.325	.0830	.100						
2/0	.365	.105	.0791						
4/0	.460	.166	.0500						

CURVE-1



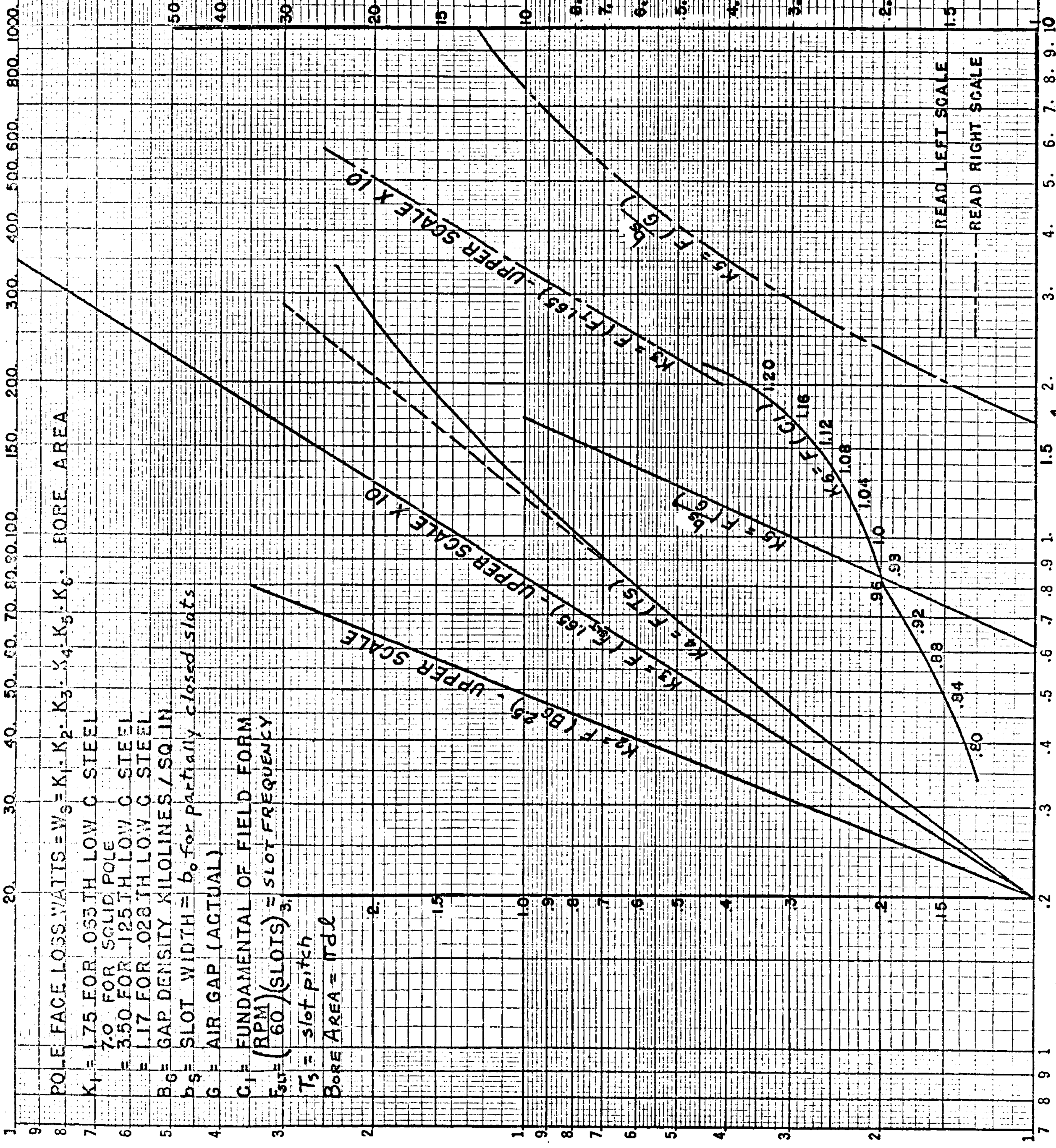
FORM 281

CURVE-2

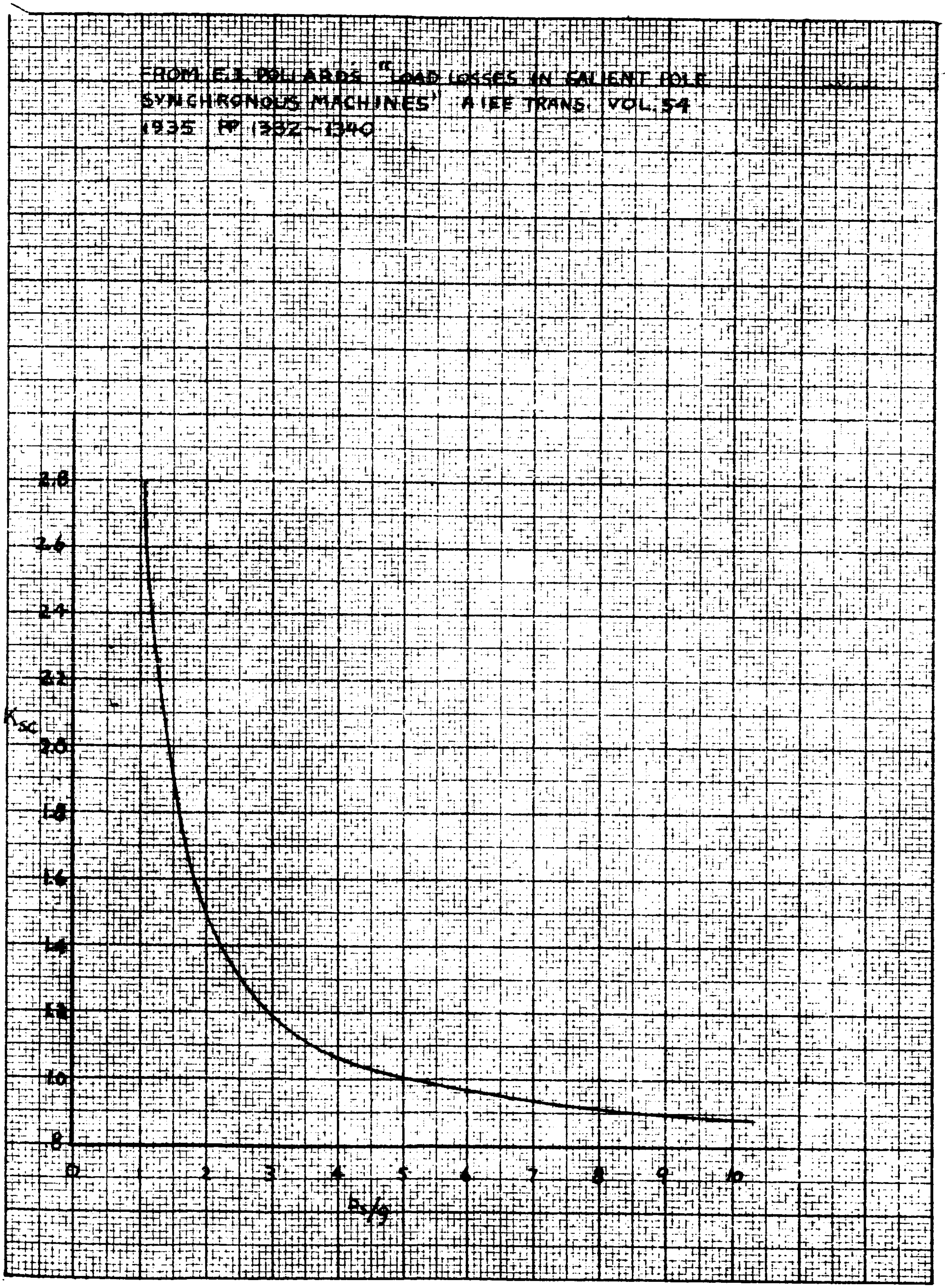
From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924, pp 262-281.

DRAWN BY J.A.T.

REFER TO ITEM (150) IN SALIENT POLE DESIGN MANUAL FOR SAMPLE USE OF THIS CURVE

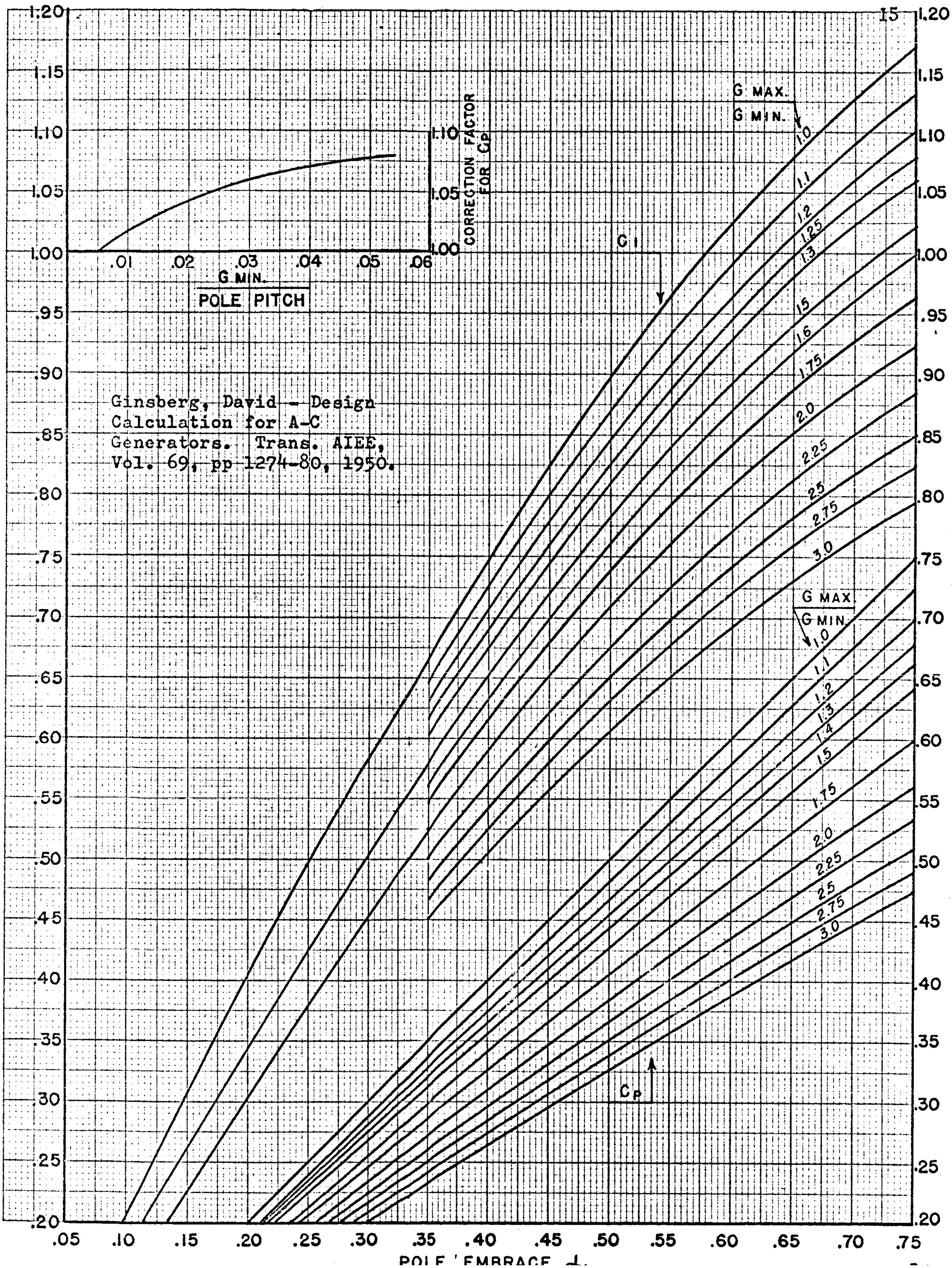


CURVE-3



FROM E.I. POLLARDS "LOAD LOSSES IN SALIENT POLE SYNCHRONOUS MACHINES" AIEE TRANS. VOL. 54 1935 PP 1332-1340
K_{sc}
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
0
2
3
4
5
6
7
8
9
10

CURVE-4



G MAX. / G MIN.
1.0
1.1
1.2
1.25
1.3
1.5
1.6
1.75
2.0
2.25
2.5
2.75
3.0
G MAX / G MIN
1.0
1.1
1.2
1.3
1.4
1.5
1.75
2.0
2.25
2.5
2.75
3.0
C_1
C_P
CORRECTION FACTOR FOR C_P
G MIN. / POLE PITCH
Ginsberg, David - Design Calculation for A-C Generators. Trans. AIEE, Vol. 69, pp 1274-80, 1950.
POLE EMBRACE

CURVE-7
NO LOAD DAMPER LOSS

$$D.L. = \frac{1.246 P n_b l_b \rho}{10^6 a_b}\left[\tau_s B_g K_p K_g\right]^2 \left[K_{f1}\left(\frac{K_{W1}}{2\lambda_s + \frac{\lambda_g}{K_{\phi 1}}}\right)^2 + K_{f2}\left(\frac{K_{W2}}{2\lambda_s+\frac{\lambda_g}{K_{\phi 2}}}\right)^2\right]$$

= LOSS IN KW

$\lambda_s = \frac{h_r}{b_r} + \lambda_t + \lambda_c$

$\lambda_g = \frac{\tau_b}{K_g g} = \frac{\tau_b}{g'}$

a_b = BAR AREA IN SQ IN.

n_b = BARS/POLE

P = NO. POLES

l_b = LENGTH BAR IN.

K_g = CARTER'S COEFFICIENT (TOTAL)

$K_p = fn(b_s/g)$, CURVE (a) ($b_s = b_o$ for partially closed slots)

K_{f1} AND $K_{f2} = fn(f_s/\rho)$ CURVE (b)

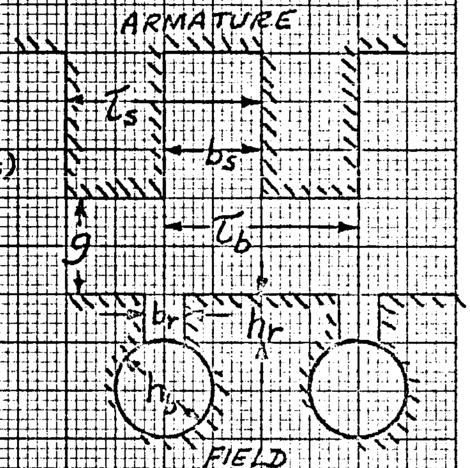
ρ = DAMPER BAR RESISTIVITY (MICROHMS PER CU. IN.)

K_{W1} AND $K_{W2} = fn(b_s/\tau_s)$, CURVE (C_1) AND (C_2)

$K_{\phi 1}$ AND $K_{\phi 2} = fn(\tau_b/\tau_s)$, CURVE ($d_1$) AND ($d_2$)

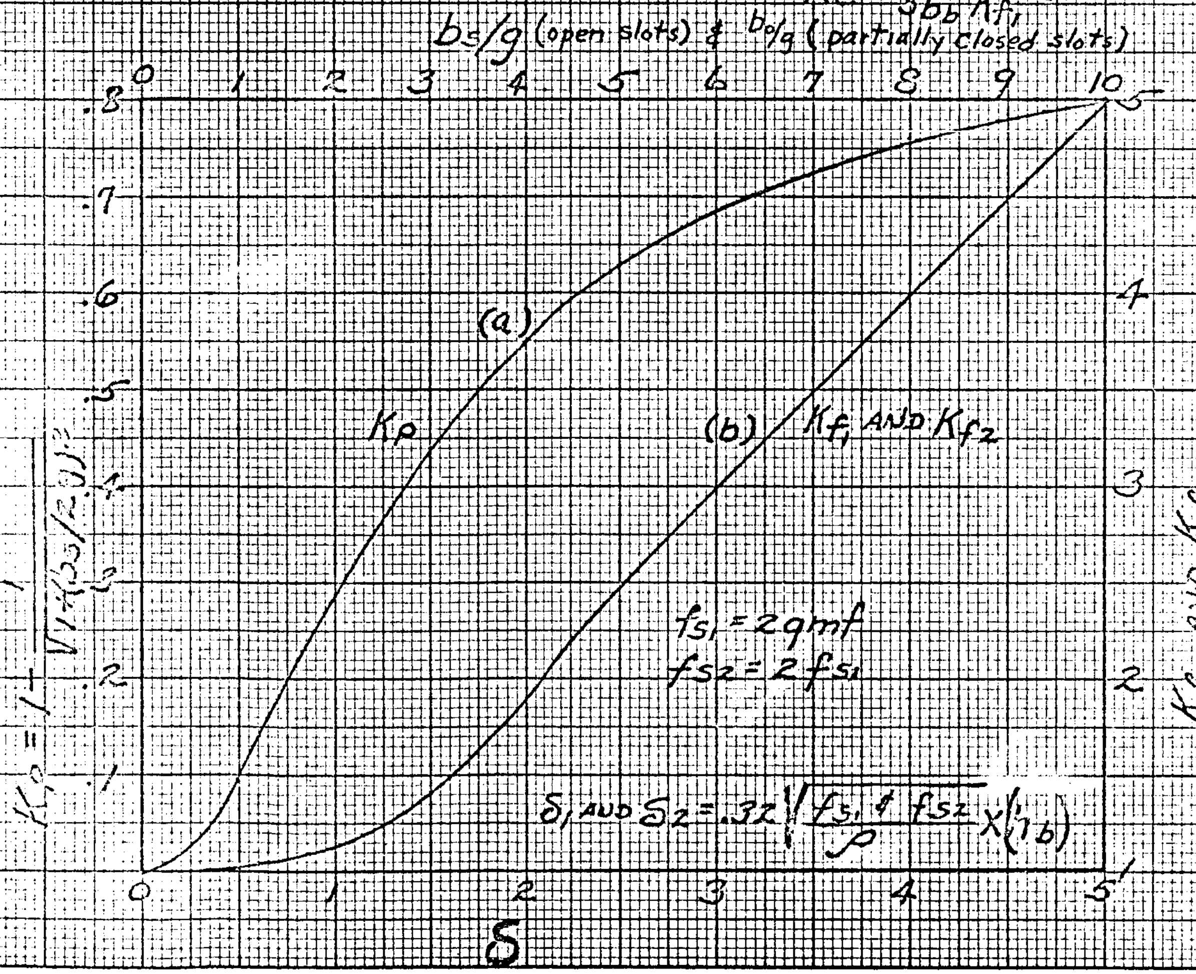
$\lambda_t = fn(b_r/gK_g)$ CURVE (e)

B_g IS IN KILOLINES PER SQ INCH



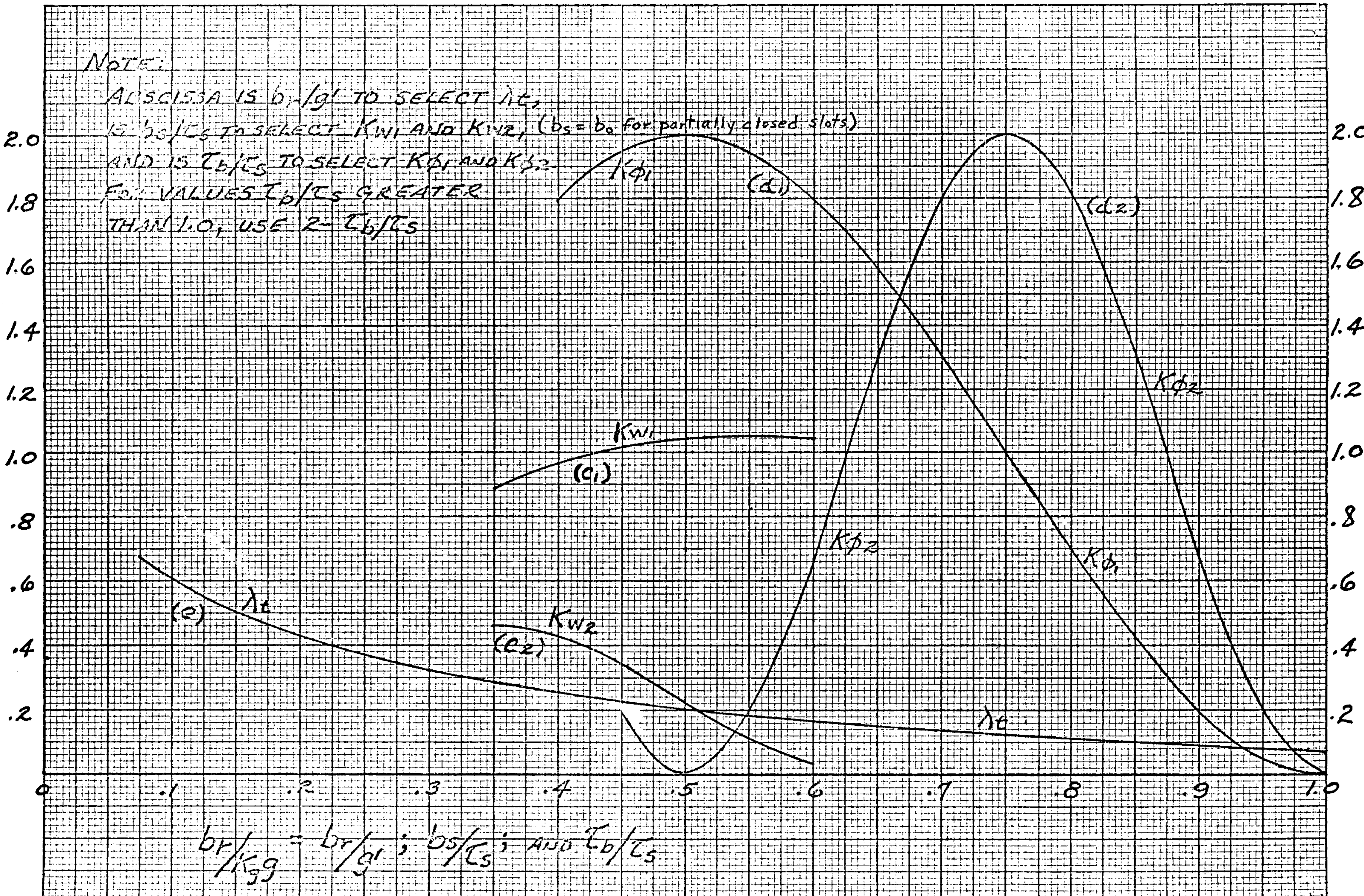
$\lambda_c = \frac{\tau_s}{K_{f1}}$ (FOR ROUND OR SQ. BARS)

$\lambda_c = \frac{h_b}{3 b_b K_{f1}}$ (FOR RECT. BARS)

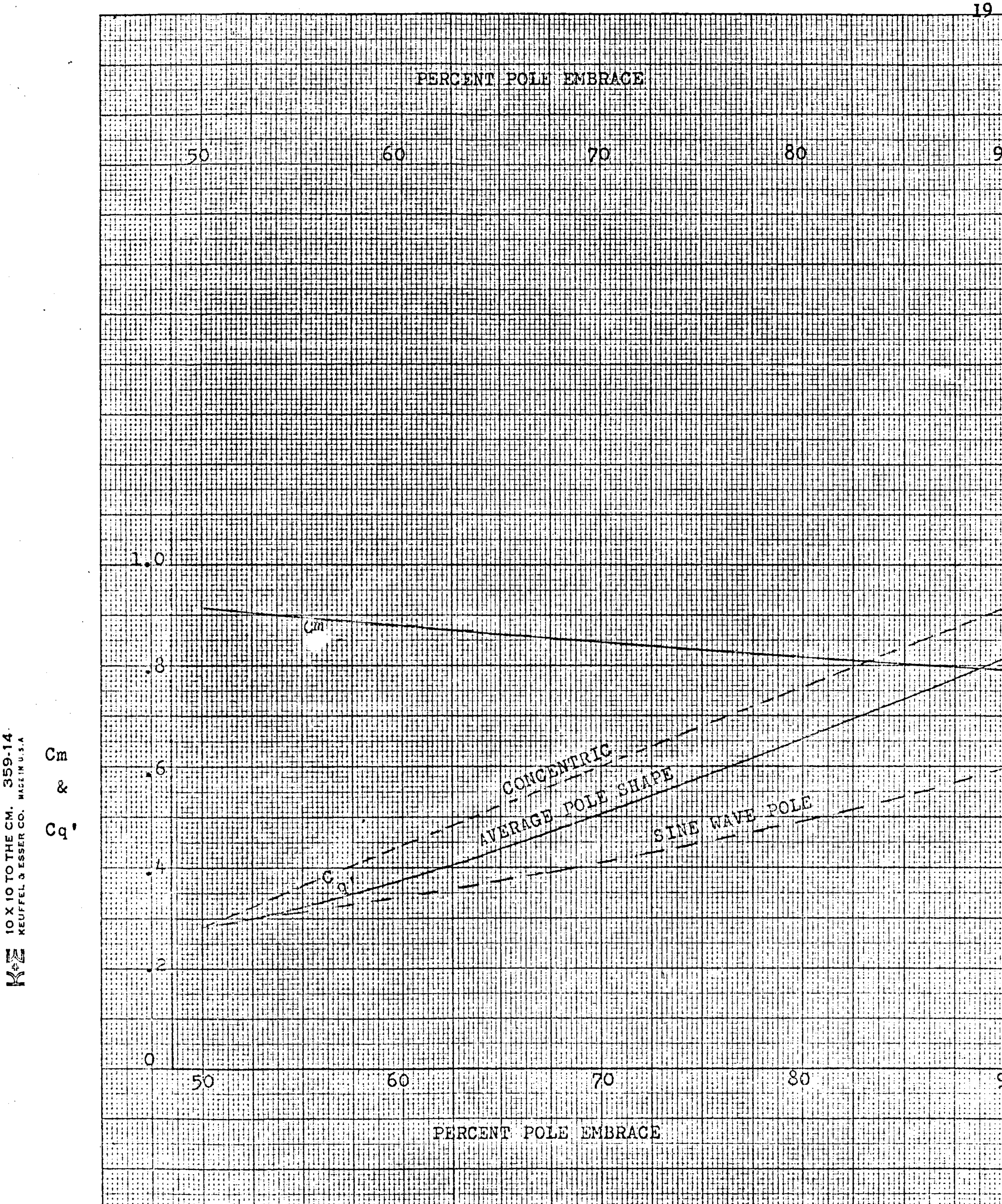


From E. I. Pollard "Calculation of No-Load Damper Winding Loss in Synchronous Machines", AIEE Vol. 51, 1932, pp 477-81.

CURVE-8

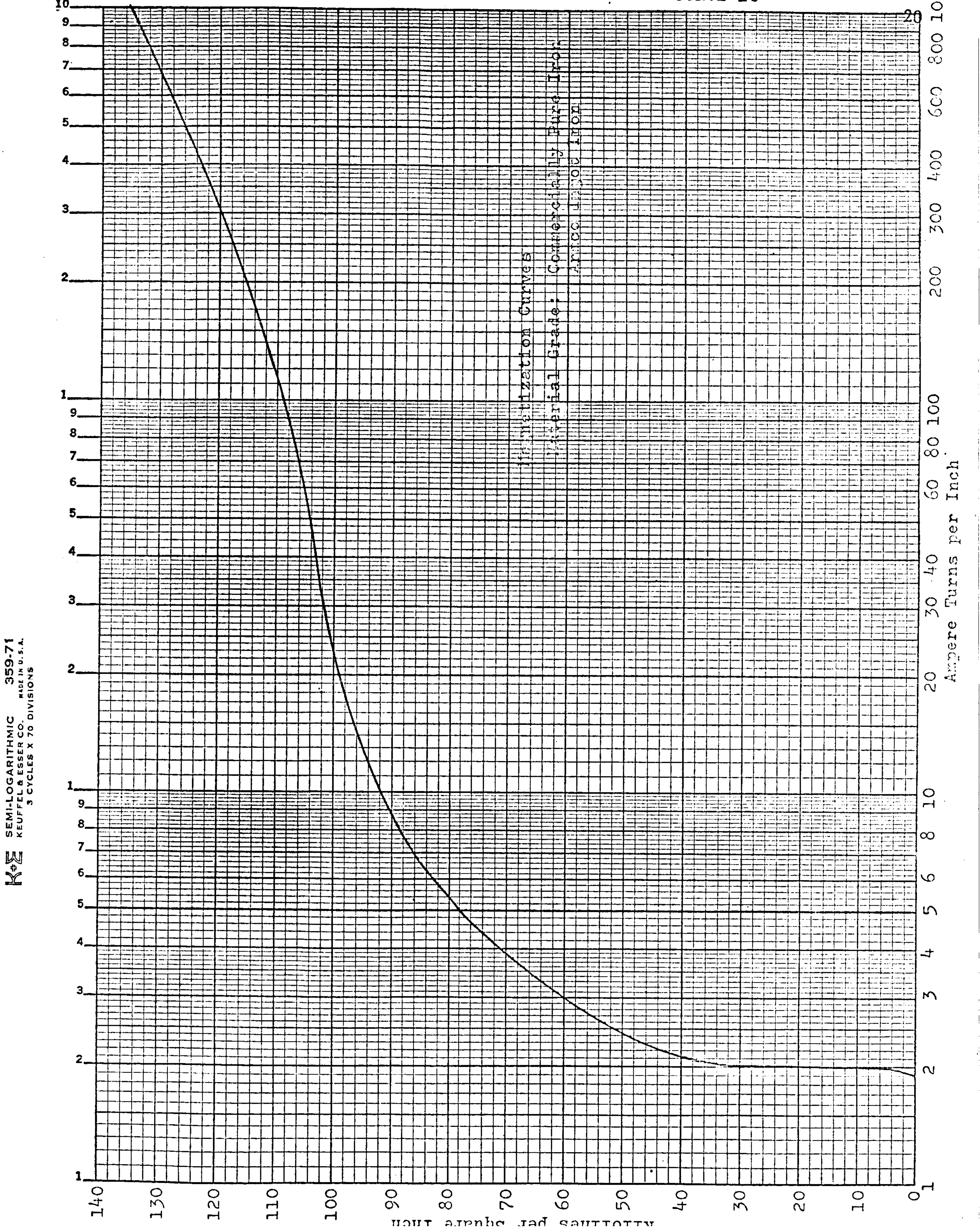

NOTE:
ABSCISSA IS br/g' TO SELECT λt,
IS bs/τs TO SELECT Kw1 AND Kw2, (bs = bo for partially closed slots)
AND IS τb/τs TO SELECT Kφ1 AND Kφ2.
FOR VALUES τb/τs GREATER
THAN 1.0, USE 2 - τb/τs
Kφ1
(d1)
(d2)
Kφ2
Kw1
(c1)
(e)
λt
Kw2
(e2)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
br/Kg g = br/g' ; bs/τs ; AND τb/τs

CURVE-9



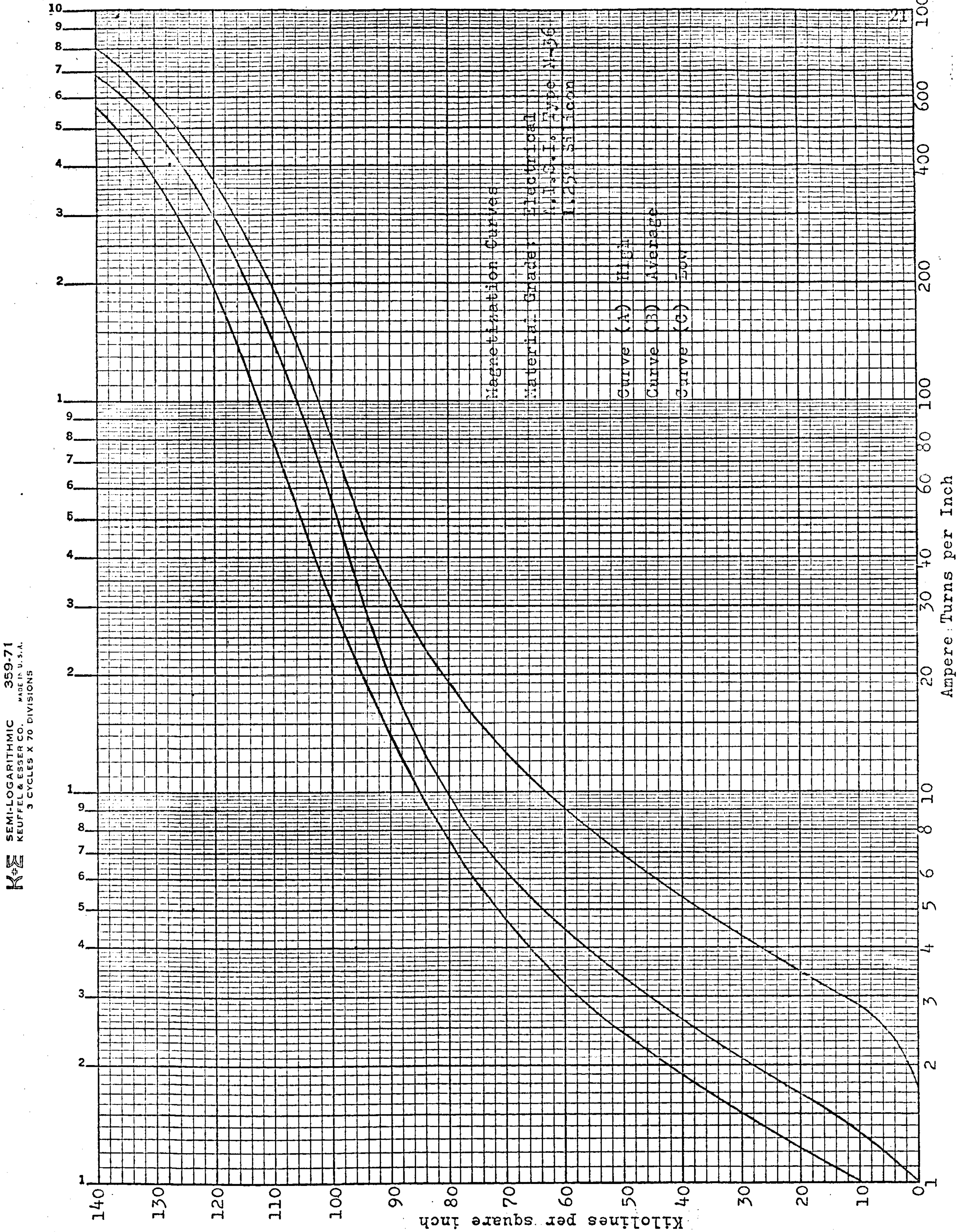
PERCENT POLE EMBRACE
50
60
70
80
90
1.0
.8
.6
.4
.2
0
Cm
CONCENTRIC
AVERAGE POLE SHAPE
SINE WAVE POLE
Cq'
PERCENT POLE EMBRACE
Cm & Cq'
SALIENT POLE MACHINE CONSTANTS C_m $C_{q'}$

CURVE 10



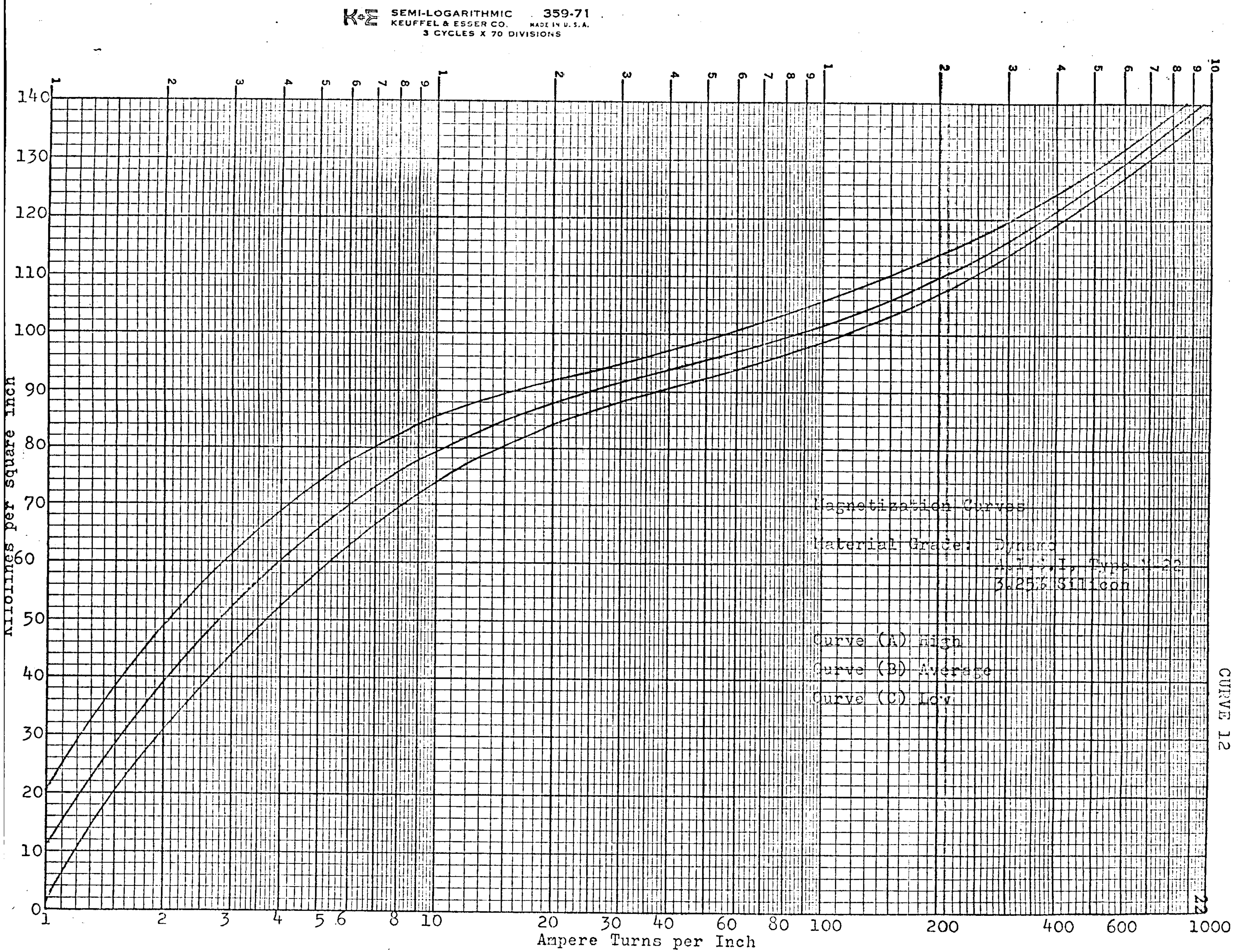
Magnetization Curves
Material Grade: Commercially Pure Iron
Armco Ingot Iron
Ampere Turns per Inch
Kilolines per Square Inch
SEMI-LOGARITHMIC 359-71
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 70 DIVISIONS

CURVE 11



Magnetization Curves
Material Grade: Electrical
A.I.S.I. Type M-36
1.25% Silicon
Curve (A) High
Curve (B) Average
Curve (C) Low
Ampere Turns per Inch
Kilolines per square inch
1000
600
400
200
100
80
60
40
30
20
10
8
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
SEMI-LOGARITHMIC 359-71
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 70 DIVISIONS

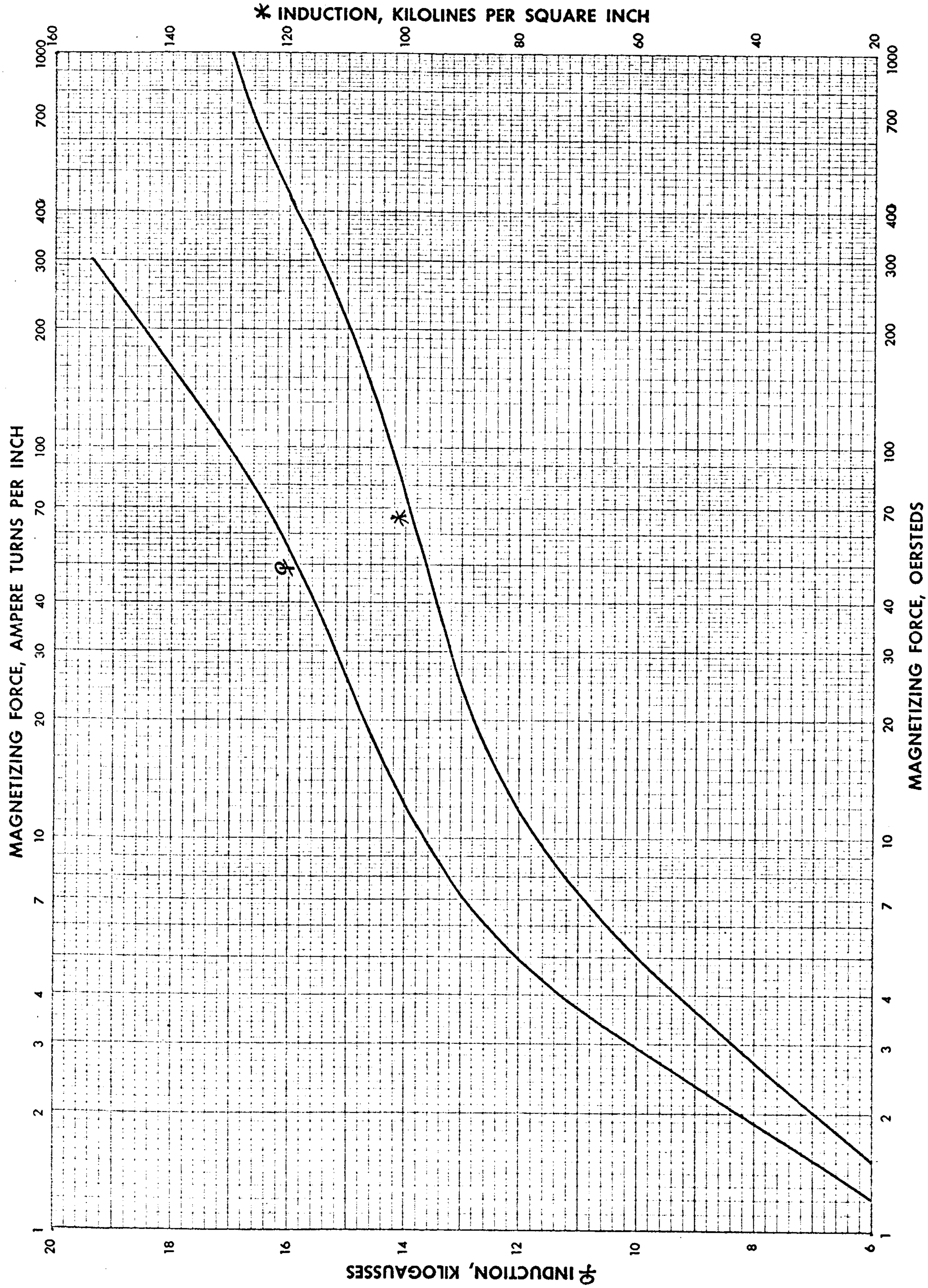
CURVE 12



SEMI-LOGARITHMIC 359-71
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 70 DIVISIONS
Kilolines per square inch
Ampere Turns per Inch
Magnetization Curves
Material Grade: Dynamo
3.25% Silicon
Curve (A) High
Curve (B) Average
Curve (C) Low

CURVE 13

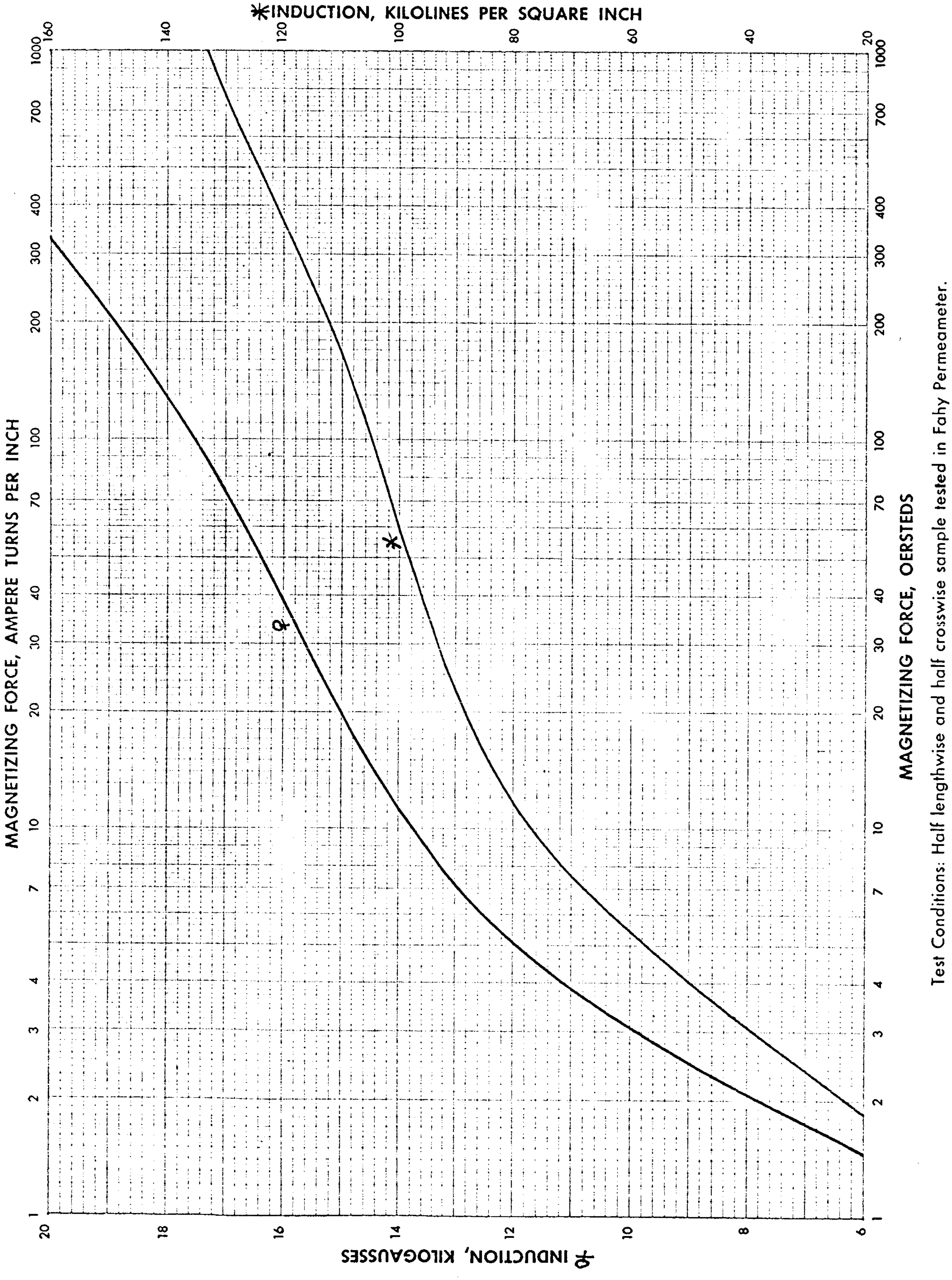
USS DYNAMO — 26 GAGE
Hot Rolled Sheets
DC MAGNETIZATION



Test Conditions: Half lengthwise and half crosswise sample tested in Fahy Permeameter.

CURVE 14

USS ELECTRICAL — 24 GAGE
Cold Reduced Coils or Sheets
DC MAGNETIZATION



SALIENT-POLE WOUND-POLE SYMBOLS

Calculation Location	Symbol	Explanation
(78)	A	Ampere conductors per inch of stator periphery
(46)	a_c	Strand area (stator)
(89)	a_{cf}	Field conductor area
(85)	a_p	Pole area
(20)	B	Density
(128)	B_c	Core density
(125)	B_g	Gap density
(140)	B_p	Pole density no load
(163)	B_{p1}	Pole density full load
(127)	B_T	Tooth density
(89)	b_{bo}	Width of slot opening (damper)
(89)	b_{b1}	Width of rectangular slot (damper)
(76)	b_h	Pole head width
(22)	b_o	Width of slot opening (stator)
(76)	b_p	Pole body width
(22)	b_s	Stator slot dimension per Fig. 1
(15)	b_v	Width of duct
(22)	b_1	Stator slot dimensions per Fig. 1
(22)	b_2	
(22)	b_3	

Calculation Location	Symbol	Explanation
(74)	C_m	Demagnetizing factor
(73)	C_p	Average/maximum field form
(75)	C_q	Cross magnetization factor
(72)	C_w	Winding constant
(71)	C_1	Ratio max. to fund.
(32)	c	Parallel circuits
(12)	D	Stator outside diameter
(11)	d	Stator inside diameter
(35)	d_b	Diameter of bender pin
(11a)	d_r	Rotor outside diameter
(3)	E	Line volts
(145)	E_F	Field volts no load
(168)	E_{FFL}	Field volts full load
(4)	E_{PH}	Phase volts
(55)	EF_{top}	Eddy factor top
(56)	EF_{bot}	Eddy factor bottom
(130)	F_c	Stator core ampere turns
(131)	F_g	Air gap ampere turns
(165)	F_{FL}	Total ampere turns full load
(142)	F_{NL}	Total ampere turns no load
(141)	F_p	Pole ampere turns at no load
(164)	F_{PL}	Pole ampere turns at full load
(136)	F_{sc}	Short circuit ampere turns

Calculation Location	Symbol	Explanation
(129)	F_t	Stator tooth ampere turns
(147)	F&W	Friction and windage
(5a)	f	Frequency
(69)	g_e	Effective air gap
(59a)	g_{max}	Maximum air gap
(22)	h_o	
(22)	h_1	
(22)	h_2	
(22)	h_3	Stator slot dimension
(22)	h_s	
(22)	h_t	
(22)	h_w	
(22)		
(89)	h_{bo}	Height of slot opening
(89)	h_{b1}	Rectangular bar thickness
(24)	h_c	Depth below slot
(76)	h_f	Pole head body
(76)	h_h	Pole head height
(37)	h_{st}	Uninsulated strand height
(38)	h'_{st}	Distance between center line of strand
(8)	I_{PH}	Phase current
(166)	I_{FFL}	Field amperes at full load

Calculation Location	Symbol	Explanation
(143)	I_{FNL}	Field amperes at no load
(146)	I^2R_R	Rotor loss
(158)	I^2R_S	Stator copper loss
(9a)	K_c	Adjustment factor
(43)	K_d	Distribution factor
(18)	K_i	Stacking factor
(44)	K_p	Pitch factor
(67)	K_s	Carter coefficient
(42)	K_{SK}	Skew factor
(2)	KVA	Machine rating
(151)	K_1	Pole face loss factor
(19)	k	Watts per lb.
(48)	L_E	End extension one turn
(113)	L_F	Field self inductance
(13)	ℓ	Gross core length
(93)	ℓ_b	Damper bar length
(136)	ℓ_{e2}	Coil extension straight portion
(76)	ℓ_n	Pole head length
(76)	ℓ_p	Pole body length
(17)	ℓ_s	Solid core length
(49)	ℓ_t	1/2 mean turn
(100)	ℓ_{tr}	Mean length of field turns
(5)	m	Number of phases

Calculation Location	Symbol	Explanation
(34)	N_{st}	Strands per conductor
(92)	n_b	Number of damper bars
(45)	n_e	Effective conductors
(99)	n_p	Number of field turns
(30)	n_s	Conductor per slot
(14)	n_v	Number of ducts
(9)	P.F.	Power factor
(6)	p	Number of poles
(23)	Q	Number of slots
(53)	$R_{ph\ (cold)}$	Stator resistance at $20^{o}C$
(54)	$R_{ph\ (hot)}$	Stator resistance at $X^{o}C$
(107)	$R_{F\ (cold)}$	Field resistance at $20^{o}C$
(108)	$R_{f\ (hot)}$	Field resistance at $X^{o}C$
(137)	SCR	Short circuit ratio
(47)	s_s	Stator current density
(144)	s_f	Field current density
(133)	T_a	Armature time constant
(134)	T_d'	Transient time constant
(135)	T_d''	Subtransient time constant
(132)	T_{do}'	Open circuit time constant
(149)	W_c	Stator core loss
(172)	W_{DFL}	Damper loss at full load

Calculation Location	Symbol	Explanation
(157)	W_{DNL}	Damper loss at no load
(171)	W_{PFL}	Pole face losses at full load
(150)	W_{PNL}	Pole face loss at no load
(170)	W_{TFL}	Stator tooth loss at full load
(148)	W_{TNL}	Stator tooth loss at no load
(98a)	V_r	Peripheral speed of rotor
(79)	X	Reactance factor
(81)	X_{ad}	Reactance direct axis
(82)	X_{aq}	Reactance quadrature axis
(83)	X_d	Synchronous reactance direct axis
(119)	X_d'	Stator transient reactance
(120)	X_d''	Subtransient reactance direct axis
(115)	X_{Dd}	Leakage reactance direct axis
(117)	X_{Dq}	Leakage reactance quadrature axis
(118)	X_{du}'	Unsaturated transient reactance
(112)	X_f	Field leakage reactance
(80)	X_ℓ	Leakage
(84)	X_q	Synchronous reactance quadrature axis
(121)	X_q''	Subtransient reactance quadrature axis
(123)	X_o	Zero sequence reactance
(122)	X_2	Negative sequence reactance
(96)	$X_D\ {}^oC$	Expected damper bar ^oC

Calculation Location	Symbol	Explanation
(103)	$X_F\,^oC$	Expected field temp. in ^oC
(50)	$X_S\,^oC$	Expected temp. stator in ^oC
(95)	ρ_D	Resistivity of damper bar at 20 ^oC
(51)	ρ_S	Resistivity of stator cond at 20 ^oC
(104)	ρ_F	Resistivity of field conductor
(138)	ϕ_ℓ	Leakage flux at no load
(160)	$\phi_{\ell\ell}$	Leakage flux at full load
(126)	ϕ_P	Flux per pole
(139)	ϕ_{PT}	Total flux per pole at no load
(162)	ϕ_{PTL}	Total flux per pole at full load
(124)	ϕ_T	Total flux
(94)	τ_b	Damper bar pitch
(41)	τ_p	Pole pitch
(26)	τ_s	Slot pitch
(27)	τ_s 1/3	Slot pitch 1/3 distance from narrowest point
(40)	τ_{sk}	Stator slot skew
(70)	λ_a	Air gap permeance
(63)	λ_E	End permeance
(86)	$\lambda_{e\ell}$	Pole end leakage permeance
(62)	λ_i	Stator conductor permeance
(88)	$\lambda_{s\ell}$	Pole side leakage permeance
(87)	$\lambda_{t\ell}$	Pole tip leakage permeance

SALIENT POLE COMPUTER DESIGN (INPUT)

MODEL__________ EWO__________ DESIGN NO(1) *1000.0*

PARAMETERS	(2)	KVA	GENERATOR KVA	30.0	1.018	RATIO MAX TO MIN OF FUND	(71)	C_1	CONSTANTS
	(3)	E	LINE VOLTS	208.0	0.0	WINDING CONSTANT	(72)	C_w	
	(4)	E_{ph}	PHASE VOLTS	120.0	.650	POLE CONST.	(73)	C_p	
	(5)	m	PHASES	3.0	0.0	END EXTENSION ONE TURN	(48)	L_E	
	(5a)	f	FREQUENCY	320.0	.84	DEMAGNETIZATION FACTOR	(74)	C_m	
	(6)	p	POLES	8.0	.52	CROSS MAGNETIZING FACTOR	(75)	C_q	
	(7)	RPM	RPM	4800.0	1.975	POLE HEAD WIDTH	(76)	b_h	ROTOR STACK
	(8)	I_{ph}	PHASE CURRENT	83.4	1.100	POLE BODY WIDTH	(76)	b_p	
	(9)	PF	POWER FACTOR	.75	.406	POLE HEAD HEIGHT	(76)	h_h	
	(9a)	K_c	ADJ. FACTOR	1.0	.979	POLE BODY HEIGHT	(76)	h_f	
	(10)		OPTIONAL LOAD POINT	.5	3.0	POLE BODY LENGTH	(76)	ℓ_p	
STATOR STACK	(11)	d	STATOR I.D.	7.25	3.0	POLE HEAD LENGTH	(76)	ℓ_n	
	(12)	D	STATOR O.D.	9.25	.71	POLE EMBRACE	(77)	α	
	(13)	ℓ	GROSS CORE LENGTH	3.0	7.18	ROTOR DIAMETER	(11a)	d_r	
	(14)	n_y	NO. OF DUCTS	0.0	.97	STACKING FACTOR (ROTOR)	(16)	K_i	
	(15)	b_y	WIDTH OF DUCT	0.0	(CURVE) 14.0	ROTOR LAM. MTR'L.	(18)		
	(16)	K_i	STACKING FACTOR (STATOR)	.92	0	WEIGHT OF ROTOR IRON	(108b)	(-)	
	(18)		STATOR LAM. MTR'L. (CURVE)	13.0	1.17	POLE FACE LOSS FACTOR	(151)	(K_1)	
	(19)	k	WATTS/LB.	15.0	.040	WIDTH OF SLOT OPENING	(89)	b_{bo}	DAMPER BAR
	(20)	B	DENSITY	77.4	.038	HEIGHT OF SLOT OPENING	(89)	h_{bo}	
STATOR SLOT	(21)		TYPE OF SLOT	2.0	.156	DAMPER BAR DIA. OR WIDTH	(90)	( )	
	(22)	b_o	SLOT OPENING	.06	0.0	RECTANGULAR BAR THICKNESS	(89)	h_{b1}	
	(22)	b_1	SLOT WIDTH TOP	0.0	0.0	RECTANGULAR SLOT WIDTH	(89)	b_{b1}	
	(22)	b_2		0.0	5.0	NO. OF DAMPER BARS	(92)	n_b	
	(22)	b_3		0.0	3.0	DAMPER BAR LENGTH	(93)	ℓ_b	
	(22)	b_s	SLOT WIDTH	.122	.403	DAMPER BAR PITCH	(94)	τ_b	
	(22)	h_o		.020	.694	RESISTIVITY OF DAMP. BAR @20°	(95)	ρ_D	
	(22)	h_1		.344	150.0	DAMPER BAR TEMP °C	(96)	X °C	
	(22)	h_2		0.0	68	NO. OF FIELD TURNS	(99)	N_p	FIELD
	(22)	h_3		0.0	10.13	MEAN LENGTH OF FLD. TURN	(100)	ℓ_{tr}	
	(22)	h_s	SLOT DEPTH	.434	.0641	FLD. COND. DIA. OR WIDTH	(101)		
	(22)	h_t		0.0	0.0	FLD. COND. THICKNESS	(102)		
	(22)	h_w		.030	150.0	FLD. TEMP IN °C	(103)	X_f°C	
	(23)	Q	NO. OF SLOTS	96.0	.694	RESISTIVITY OF FIELD COND @20°	(104)	ρ_f	
STATOR WINDING	(28)		TYPE OF WDG.	1.0	1.0	NO LOAD SAT.	(179)		
	(29)		TYPE OF COIL	1.0	0	FRICTION & WINDAGE	(147)	(F&W)	
	(30)	n_s	CONDUCTORS/SLOT	2.0					
	(31)	y	SLOTS SPANNED	10.0					
	(32)	c	PARALLEL CIRCUITS	1.0					
	(33)		STRAND DIA. OR WIDTH	.075					
	(34)	N_{st}	STRANDS/CONDUCTOR	1.0					
	(35)	d_b	DIA. OF PIN	.25					
	(36)	ℓ_{e2}	COIL EXT. STR. PORT	.25					
	(37)	h_{st}	UNINS. STRD. HT.	.162					
	(38)	h'_{st}	DIST. BTWN. C_L OF STD.	.192					
	(39)		STATOR STRAND T'KNS.	.162					
	(40)	τ_{sk}	STATOR SLOT SKEW	.0001					
	(50)	X °C	STATOR TEMP °C	150.0					
	(51)	ρ_s	RES'TVY STA. COND. @20° C	.694					
	(59)	g_{min}	MINIMUM AIR GAP	.035					
	(59a)	g_{max}	MAXIMUM AIR GAP	.047					

STATOR SLOT	POLE
DAMPER SLOT	REMARKS

DESIGNER__________ DATE__________

SUMMARY OF DESIGN CALCULATIONS – SALIENT POLE (OUTPUT)

MODEL NO. ______ EWO ______ DESIGN NO. 1000.00000

STATOR	(17) (ℓ_s)	SOLID CORE LENGTH	2.76000	1.08190	CARTER COEFFICIENT	(67) (K_s)	GAP
	(24) (h_c)	DEPTH BELOW SLOT X 2	.56600	68.33850	AIR GAP AREA	(68) (-)	
	(26) (τ_s)	SLOT PITCH	.23728	152.69103	AIR GAP PERM	(70) (λ_a)	
	(27) ($\tau_{s1/3}$)	SLOT PITCH 1/3 DIST. UP	.24676	.03786	EFFECTIVE AIR GAP	(69) (g_e)	
	(42) (K_{sk})	SKEW FACTOR	1.00000	1.01800	RATIO MAX TO FUND.	(71) (C_1)	CONSTANTS
	(43) (K_d)	DIST. FACTOR	.95765	.39823	WINDING CONST.	(72) (C_w)	
	(44) (K_p)	PITCH FACTOR	.96596	.65000	POLE CONST.	(73) (C_p)	
	(45) (n_e)	EFF. CONDUCTORS	185.46619	4.59241	END. EXT. ONE TURN	(48) (L_E)	
	(46) (a_c)	STRAND AREA	.01135	.84000	DEMAGNETIZING FACTOR	(74) (C_M)	
	(47) (S_s)	CURRENT DENSITY (STA.)	7343.32690	.52000	CROSS MAGNETIZING FCTR	(75) (C_q)	
	(49) (ℓ_t)	1/2 MEAN TURN	7.59241	679.03797	AMP COND/IN	(78) (A)	REACTANCE
	(53) (R_{ph})	COLD STA. RES. @20°C	.02971	.87672	REACTANCE FACTOR	(79) (X)	
	(54) (R_{ph})	HOT STA. RES. @X°C	.04501	7.76606	LEAKAGE REACTANCE	(80) (X_ℓ)	
	(55) (EF_{top})	EDDY FACTOR TOP	1.16467	114.47347	REACTANCE DIRECT AXIS	(81) (X_{ad})	
	(56) (EF_{bot})	EDDY FACTOR BOT	1.02326	69.61152	REACTANCE QUAD AXIS	(82) (X_{aq})	
	(62) (λ_i)	STATOR COND. PERM.	3.43609	122.23953	SYN REACT DIRECT AXIS	(83) (X_d)	
	(63) (λ_e)	END PERM.	5.42192	77.37758	SYN REACT QUAD AXIS	(84) (X_q)	
	(65) ( )	WT. OF STA COPPER	5.31106	14.33483	FIELD LEAKAGE REACT	(112) (X_f)	
	(66) ( )	WT. OF STA IRON	16.27519	.18440	FIELD SELF INDUCTANCE	(113) (L_f)	
ROTOR	(41) (τ_p)	POLE PITCH	2.84743	4.33170	LEAKAGE REACT DIRECT AX.	(115) (X_{Dd})	
	(85) (a_p)	POLE AREA	3.20100	5.35257	LEAKAGE REACT QUAD AX.	(117) (X_{Dq})	
	(86) ($\lambda_{e\ell}$)	POLE END LEAK PERM.	.41800	22.10089	UNSAT. TRANS. REACT	(118) (X'_{du})	
	(87) ($\lambda_{t\ell}$)	POLE TIP LEAK PERM.	.64832	19.44878	SAT. TRANS. REACT	(119) (X'_d)	
	(88) ($\lambda_{s\ell}$)	POLE SIDE LEAK PERM.	.80990	12.09776	SUB.TRANS REACT DIRECT AX.	(120) (X''_d)	
	(89) (a_{CF})	FLD COND. AREA	.00322	13.11863	SUB.TRANS REACT QUAD AX.	(121) (X''_q)	
	(90) (R_F)	COLD FLD RES @20°C	1.18771	12.60819	NEG SEQUENCE REACT	(122) (X_2)	
	(91) (R_F)	HOT FLD RES @X°C	1.79930	3.30450	ZERO SEQUENCE REACT	(123) (X_o)	
	(108a) ( )	WT OF FLD COPPER	5.69599	3520.25190	TOTAL FLUX	(124) (ϕ_T)	MAGNETIZATION
	(108b) ( )	WT OF ROTOR IRON	.00000	286.02046	FLUX PER POLE	(126) (ϕ_p)	
	(98a) (V_r)	PERIPHERAL SPEED	9029.56800	51.51198	GAP DENSITY	(125) (B_g)	
TIME CONSTANTS	(132) (T_{do})	OPEN CIR. TIME CONST.	.10248	106.49226	TOOTH DENSITY	(127) (B_T)	
	(133) (T_a)	ARM TIME CONST.	.00200	91.54646	CORE DENSITY	(128) (B_c)	
	(134) (T'_d)	TRANS TIME CONST.	.01630	67.69566	TOOTH AMPERE TURNS	(129) (F_t)	
	(135) (T''_d)	SUB TRAN TIME CONST.	.00500	25.81124	CORE AMPERE TURNS	(130) (F_c)	
	(136) (F_{sc})	SHORT CIR NI	747.32558	611.36163	GAP AMPERE TURNS	(131) (F_g)	
	(137) (SCR)	SHORT AIR RATIO	1.03001				

VARIABLE LOAD — PERCENT LOAD	0		100	150	200	OPTIONAL
(ϕ_ℓ) (138) LEAK FLUX	27.131	($\phi_{\ell\ell}$) (160)	49.621	62.294	75.252	37.569
(ϕ_{pt}) (139) POLE FLUX	313.151	(ϕ_{ptl}) (162)	353.503	377.720	404.910	332.960
(B_p) (140) POLE DENSITY	97.829	(B_{pl}) (163)	110.435	118.000	126.494	104.017
(F_p) (141) POLE NI	68.669	(F_{pl}) (164)	241.300	442.669	835.502	130.953
(F_{nl}) (142) TOTAL NI	823.071	(F_{fl}) (165)	1621.979	2176.268	2929.955	1176.017
(I_{fnl}) (143) FIELD AMPS	12.103	(I_{ffl}) (166)	23.852	32.003	43.087	17.294
(S_F) (144) CUR. DENS. (FLD)	3759.001	(—) (167)	7407.650	9939.114	13381.236	5370.925
(E_F) (145) FIELD VOLTS	14.376	(E_{ffl}) (168)	42.918	57.584	77.527	31.117
(I^2R_r) (146) ROTOR LOSS	174.007	(I^2R_r) (169)	1023.708	1842.938	3340.471	538.162
(F & W) (147) F & W LOSS	347.291	(F & W) (147)	347.291	347.291	347.291	347.291
(W_{tnl}) (148) STA TOOTH LOSS	184.539	(W_{tfl}) (170)	234.722	288.655	359.285	198.950
(W_c) (149) STA CORE LOSS	404.227	(W_c) (149)	404.227	404.227	404.227	404.227
(W_{pnl}) (150) POLE FACE LOSS	105.017	(W_{pfl}) (171)	114.675	126.748	143.650	107.432
(W_{dnl}) (157) DAMPER LOSS	.256	(W_{dfl}) (172)	.345	.382	.433	.324
(I^2R_s) (158) STATOR CU LOSS	.000	(I^2R_s) (173)	939.209	2113.220	3756.837	234.802
(—) (158) EDDY LOSS	.000	(—) (173a)	88.248	198.558	352.992	22.062
(—) (159) TOTAL LOSSES	1215.340	(—) (174)	3152.428	5322.023	8705.189	1853.253
(—) (—) RATING (KW)	.000	(—) (175)	22534.013	33801.020	45068.026	11267.007
(—) (—) RATING & LOSSES	1215.340	(—) (176)	25686.441	39123.043	53773.215	13120.260
(—) (—) PERCENT LOSSES	100.000	(—) (177)	12.272	13.603	16.188	14.125
(—) (—) PERCENT EFF.	.000	(—) (178)	87.727	86.396	83.811	85.874

REMARKS

DESIGNER

DATE

NO LOAD SATURATION OUTPUT SHEET

ITEMS / VOLTS	(179) (—) VOLTS (185) (F'_s) STATOR A.T.	(180) (F'_g) AIR GAP A.T. (186) (ϕ'_ℓ) LEAKAGE FLUX	(181) (B'_t) TOOTH DENSITY (187) (ϕ'_{pt}) TOTAL FLUX/POLE	(182) (F'_t) TOOTH A.T. (188) (B'_p) TOOTH DENSITY	(183) (B'_c) CORE DENSITY (189) (F'_p) POLE A.T.	(184) (F'_c) CORE A.T. (190) (F'_{nl}) TOTAL A.T. (N.L.)
80%	166.27200 14.59590	489.08930 18.08733	85.19380 246.90370	7.29726 77.13330	73.23716 14.31810	7.298 28.914
90%	187.05600 33.12066	550.22547 20.94796	95.84303 278.36637	21.14996 86.96231	82.39181 25.71249	11.970 58.833
100%	207.84000 93.50690	611.36163 25.31182	106.49226 311.33228	67.69566 97.26094	91.54646 64.89074	25.811 158.397
110%	228.62400 231.00817	672.49779 32.44489	117.14149 347.06740	158.70457 108.42467	100.70111 203.36754	72.303 434.375
120%	249.40800 479.03354	733.63396 43.54689	127.79071 386.77144	301.98336 120.82831	109.85575 544.53846	177.050 1023.572
130%	270.19200 747.42263	794.77012 55.38014	138.43994 427.20674	394.41868 133.46039	119.01040 1193.19100	353.003 1940.613
140%	TOOTH DENSITY SATURATED					
150%						
160%						

(1)	--	DESIGN NUMBER - To be used for filing purposes
(2)	KVA	GENERATOR KVA
(3)	E	LINE VOLTS
(4)	E_{PH}	PHASE VOLTS - For 3 phase, delta connected generator $E_{PH} = \frac{\text{(Line Volts)}}{\sqrt{3}} = \frac{(3)}{\sqrt{3}}$ For 3 phase, wye connected generator $E_{PH} = \text{(Line Volts)} = (3)$
(5)	m	PHASES - Number of
(5a)	f	FREQUENCY - In cycles per second
(6)	P	POLES - Number of
(7)	RPM	SPEED - In revolutions per minute
(8)	I_{PH}	PHASE CURRENT - In amperes at rated load
(9)	P.F.	POWER FACTOR - Given in per unit
(9a)	K_c	ADJUSTMENT FACTOR - When P.F. = 0. to .95 set $K_c = 1.$; when P.F. = .95 to 1. set $K_c = 1.05$
(10)	--	LOAD POINTS - The computer program is set up to have the 0.%, 100%, 150%, 200% load points as standard outputs. There is an additional space available on the output sheet for one optional load point. This optional

load point will be the designer's choice and can be selected anywhere in the range of 0 to 200% load. When an optional load calculation is required insert the per unit load value on the input sheet. The optional load point will be calculated in addition to the standard points listed above. If only the standard points are required, insert 0. on input sheet. For example, insert .33 on input sheet when the optional load calculation for 33% load is required in addition to the standard points.

(11)	d	STATOR PUNCHING I.D. - The inside diameter of the stator punching in inches
(11a)	d_r	ROTOR PUNCHING O.D. - The outside diameter of the rotor punching in inches
(12)	D	PUNCHING O.D. - The outside diameter of the stator punching in inches
(13)	ℓ	GROSS CORE LENGTH - In inches
(14)	n_v	RADIAL DUCTS - Number of
(15)	b_v	RADIAL DUCT WIDTH - In inches
(16)	K_i	STACKING FACTOR - This factor allows for the coating (core plating) on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in Table IV.

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K_i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

TABLE IV

(17) ℓ_s SOLID CORE LENGTH - The solid length is the gross length times the stacking factor. If ventilating ducts are used, their length must be subtracted from the gross length also.

$$\ell_s = (K_i)\left[(\ell) - (n_v)(b_v)\right] = (16)\left[(13) - (14)(15)\right]$$

(18) -- LAMINATION MATERIAL - This input is used in selecting the proper magnetization curve. Where curves are available on card decks, use the proper identifying code. Where card decks are not available, submit as an auxiliary input, 29 points of the curve to be used (start first reading at 0). These points are the ampere turns per inch for each five units on the density scale, where 1 unit is 1 kiloline/in^2. Refer to curves 10, 11, 12 for standard magnetization curves. Submit separate magnetization curves for stator and rotor when different materials are used. Separate spaces are provided on input sheet for stator material and rotor material.

When the magnetization curve is not available on card decks insert 0. on input sheet and provide 29 point of the curve to be used as outlined previously in this paragraph. When the magnetization curve is available on existing card decks, and a coding system is available to identify each curve, then insert the proper code number on the input sheet. Since curves are available on card decks they have been coded as follows: 1.0 = curve 10; 2.0 = curve 11-high; 2.1 = curve 11-average; 2.2 = curve 11-low; 3.0 = curve 12-high; 3.1 = curve 12-average; 3.2 = curve 12-low. Once a curve has been submitted, the card deck should be coded and stored for future use. An index of coded magnetization curves should be published from time to time to bring records up to date.

(19)	k	<u>WATTS/LB</u> - Core loss per lb of lamination material. Must be given at the density specified in (20).
(20)	B	<u>DENSITY</u> - This value must correspond to the density used in item (19) to pick the watts/lb. The density that is usually used is 77.4 kilolines/in^2.

(21)	1
	2
	3
	4
	5
		<u>TYPE OF STATOR SLOT</u> - Refer to Figure 1, Page 8 for type of slot
		For (a) slot use 1. as an input
		For (b) slot use 2. as an input
		For (c) slot use 3. as an input
		For (d) slot use 4. as an input
		Type 5. is not a slot but instead a particular situation for an open slot where the winding has only one conductor per slot.

(22)	b_0, b_1, b_2, b_3, b_s, h_0, h_1, h_2, h_3, h_s, h_t, h_w	ALL SLOT DIMENSIONS - Given in inches per Figure 1, page 8. Where the dimension does not apply to the slot being used, insert 0. on input sheet.
(23)	Q	STATOR SLOTS - Number of
(24)	h_c	DEPTH BELOW SLOTS - The depth of the stator core below the slots. Due to mechanical strength reasons, h_c should never be less than 70% of h_s. $h_c = \frac{(D) - \boxed{(d) + 2(h_S)}}{2} = \frac{(12) - \boxed{(11) + 2(22)}}{2}$
(25)	q	SLOTS PER POLE PER PHASE $q = \frac{(Q)}{(P)(m)} = \frac{(23)}{(6)(5)}$
(26)	τ_s	STATOR SLOT PITCH $\tau_s = \frac{\pi(d)}{Q} = \frac{\pi(11)}{(23)}$

(27)	$\tau s1/3$	STATOR SLOT PITCH - 1/3 distance up from narrowest section For slot (a), (b), (c), and (e) $\tau s1/3 = \frac{\pi\left[(d) + .66(h_s)\right]}{(Q)} = \frac{\pi\left[(11) + .66(22)\right]}{(23)}$ For slot (d) $\frac{\pi\left[(d) + 2(h_0) + 1.32(b_s)\right]}{(Q)} = \frac{\pi\left[(11) + 2(22) + 1.32(22)\right]}{(23)}$
(28)	--	TYPE OF WINDING - Record whether the connection is "wye" or "delta". For "wye" conn use 1. for input. For "delta" use 0. for input
(29)	--	TYPE OF COIL - Record whether random wound or formed coils are used. For random wound coils use 0. for input. For formed coils use 1. for input.
(30)	n_s	CONDUCTORS PER SLOT - The actual number of conductors per slot. For random wound coils use a space factor of 75% to 80%. Where space factor is the percent of the total slot area that is available for insulated conductors after all other insulation areas have been subtracted out.
(31)	y	THROW - Number of slots spanned. For example, with a coil side in slot 1 and the other coil side in slot 10, the throw is 9.

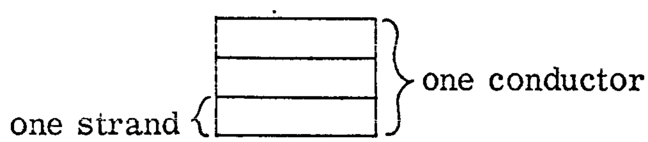
(31a) PERCENT OF POLE PITCH SPANNED - Ratio of the number of slots spanned to the number of slots in a pole pitch

$$= \frac{(Y)}{(m)\,(q)} = \frac{(31)}{(5)\,(25)}$$

(32) C PARALLEL PATHS, No. of - Number of parallel circuits per phase

(33) -- STRAND DIA OR WIDTH - In inches. For round wire, use strand diameter. For rectangular wire, use strand width.

(34) N_{ST} NUMBER OF STRANDS PER CONDUCTOR IN DEPTH - Applies to rectangular wire. In order to have a more flexible conductor and reduce eddy current loss a stranded conductor is often used. For example, when the space available for one conductor is .250 width x .250 depth, the actual conductor can be made up of 2 or 3 strands in depth as shown



For a more detailed explanation refer to section titled "Effective Resistance and Eddy Factor" in the Derivations in Appendix.

(35) d_b DIAMETER OF BENDER PIN in inches - This pin is used in forming coils

(36) ℓ_{e2} COIL EXTENSION BEYOND CORE in inches - Straight portion of coil that extends beyond stator core

(37) h_{ST} HEIGHT OF UNINSULATED STRAND in inches

(38)	h'_{ST}	DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH in inches
(39)	--	STATOR COIL STRAND THICKNESS in inches - For rectangular conductors only. For round wire insert 0. on input sheet.
(40)	τ_{SK}	SKEW - Stator slot skew in inches at stator I.D.
(41)	τ_P	POLE PITCH in inches $$\frac{\pi(d)}{(P)} = \frac{\pi(11)}{(6)}$$
(42)	K_{SK}	SKEW FACTOR - The skew factor is the ratio of the voltage induced in the coils to the voltage that would be induced if there were no skew $$K_{SK} \frac{\sin\left[\frac{\pi(\tau_{SK})}{2(\tau_P)}\right]}{\frac{\pi(\tau_{SK})}{2(\tau_P)}} = \frac{\sin\left[\frac{\pi(40)}{2(41)}\right]}{\frac{\pi(40)}{2(41)}}$$
(43)	K_d	DISTRIBUTION FACTOR - The distribution factor is the ratio of the voltage induced in the coils to the voltage that would be induced in the coils if the winding were concentrated in a single slot. See Table 2 for compilation of distribution factors for the various harmonies. $$K_d = \frac{\sin\left[\frac{(q)(\alpha_s)}{2}\right]}{(q)\sin\frac{(\alpha_s)}{2}} \quad \text{where } \alpha_s = \frac{180^{o}}{(m)(q)}$$

$$\therefore K_d = \frac{\sin\left[90^\circ/(m)\right]}{(q)\sin\left[90^\circ/(m)(q)\right]} = \frac{\sin\left[90^\circ/(5)\right]}{(25)\sin\left[90^\circ/(5)\times(25)\right]} \text{ For } (25) = \text{Integer}$$

or

$$K_d = \frac{\sin\left[N\alpha(m)/2\right]}{N\sin\left[\alpha(m)/2\right]} \text{ where } N = \text{Integer} = \frac{(Q)}{(m)(P)} \times \text{Integer} \ \& \ \alpha m = \frac{180^\circ}{N \times (m)}$$

$$\therefore K_d = \frac{\sin\left[90^\circ/(m)\right]}{N\sin\left[90^\circ/N(m)\right]} = \frac{\sin\left[90^\circ/(5)\right]}{N\sin\left[90^\circ/N\times(5)\right]} \text{ For } (25) = \text{Integer}$$

(44)	K_P	PITCH FACTOR - The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil. See Table 1 for compilation of the pitch factors for the various harmonics. $K_P = \sin\left[\frac{(Y)}{(m)(q)} \times 90^\circ\right] = \sin\left[\frac{(31)}{(5)(25)} \times 90^\circ\right]$
(45)	n_e	TOTAL EFFECTIVE CONDUCTORS - The actual number of effective series conductors in the stator winding taking into account the pitch and skew factors but not allowing for the distribution factor. $n_e = \frac{(Q)(n_S)(K_P)(K_{SK})}{(C)} = \frac{(23)(30)(44)(42)}{(32)}$
(46)	a_c	CONDUCTOR AREA OF STATOR WINDING in (inches)^2 - The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii. If (39) = 0 then $a_c = .25\pi(\text{Dia})^2 = .25\pi(33)^2$

If (39) $\neq$ 0 then $a_c = (N_{ST}) \left[(\text{strand width}) (\text{strand depth}) - (.858\, r_c^{\,2}) \right]$

$$= (34) \left[(33)\ (39) - \{.858\, r_c^{\,2}\} \right]$$

where $.858\, r_c^{\,2}$ is obtained from Table V below.

(39)	(33) .188	.189 (33) .75	(33) .751
.050	.000124	.000124	.000124
.072	.000210	.000124	.000124
.125	.000210	.00084	.000124
.165	.000840	.00084	.003350
.225	.001890	.00189	.003350
.438	--	.00335	.007540
.688	--	.00754	.01340
--	--	.03020	.03020

TABLE V

(47) S_S CURRENT DENSITY - Amperes per square inch of stator conductor

$$S_S = \frac{(I_{PH})}{(C)(a_c)} = \frac{(8)}{(32)(46)}$$

(48) L_E END EXTENSION LENGTH in inches - Can be an input or output.

For L_E to be output, insert 0. on input sheet.

For L_E to be input, calculate per following:

When (29) = 0 then:

$$L_E = \frac{.5 + K_T \pi y \left[d + h_s \right]}{Q} = .5 + \frac{\left[\begin{array}{l} 1.3 \text{ If } (6) = 2 \\ 1.5 \text{ If } (6) = 4 \\ 1.7 \text{ If } (6) > 4 \end{array}\right] \pi (31) \left[(11) + (22) \right]}{(23)}$$

When (29) = 1, then:

$$L_E = 2\ell_{e2} + \pi\left[\frac{h_1}{2} + \text{dia}\right] + y\left[\frac{t_s^{\,2}}{\sqrt{t_s^{\,2} - b_s^{\,2}}}\right]$$

$$= 2 \times (36) + \pi\left[\frac{(22)}{2} + (35)\right] + (31)\left[\frac{(26)^2}{\sqrt{(26)^2 - (22)^2}}\right]$$

(49) ℓ_t 1/2 MEAN TURN - The average length of one conductor in inches

$$\ell_t = (\ell) + (L_E) = (13) + (44)$$

(50) $X_s\,^\circ C$ STATOR TEMP $^\circ$C. - Input temp at which F.L. losses will be calculated. No load losses and cold resistance will be calculated at 20°C.

(51) ρ_s RESISTIVITY OF STATOR WINDING - In micro ohm-inches @ 20°C. If tables are available using units other than that given above, use Table VI for conversion to ohm-inches.

ρ	ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm =	1.000	0.3937	6.015×10^6
1 ohm-in =	2.540	1.000	1.528×10^7
1 ohm-cir mil/ft =	1.662×10^{-7}	6.545×10^{-8}	1.000

TABLE VI
Conversion Factors for Electrical Resistivity

(52) ρ_S (hot) RESISTIVITY OF STATOR WINDING - Hot at $X_s\,^\circ$C in micro ohm-inches

$$\rho_{S(hot)} = (\rho_S)\left[\frac{(X_s\,^\circ C) + 234.5}{254.5}\right] = (51)\left[\frac{(50) + 234.5}{254.5}\right]$$

(53) R_{SPH} (cold) **STATOR RESISTANCE/PHASE** - Cold @ 20°C in ohms

$$R_{SPH(cold)} = \frac{(\rho_s)(n_s)(Q)(\ell_t)}{(m)(a_c)(C)^2} = \frac{(51)(30)(23)(49)}{(5)(46)(32)^2}$$

(54) R_{SPH} (hot) **STATOR RESISTANCE/PHASE** - Calculated @ X°C in ohms

$$R_{SPH(hot)} = \frac{(\rho_{s\ hot})(n_s)(Q)(\ell_t)}{(m)(a_c)(C)^2} = \frac{(52)(30)(23)(49)}{(5)(46)(32)^2}$$

(55) EF (top) **EDDY FACTOR TOP** - The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine.

$$EF_{top} = 1 + \left\{ .584 + \left[\frac{N_{st}^2 - 1}{16}\right]\left[\frac{h'_{st}\ell}{h_{st}\ell_t}\right]^2 \right\} 3.35 \times 10^{-3} \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{S\,hot}) \times 10^6}\right]^2$$

$$= 1 + \left\{ .584 + \left[\frac{(34)^2 - 1}{16}\right]\left[\frac{(38)(13)}{(37)(49)}\right]^2 \right\} 3.35 \times 10^{-3} \left[\frac{(37)(30)(5a)(46)}{(22)(52)\,10^6}\right]^2$$

(56) EF (bot) **EDDY FACTOR BOTTOM** - The eddy factor of the bottom coil at the expected operating temperature of the machine

$$EF_{(bot)} = (EF_{(top)}) - 1.677 \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{S\,hot})\,10^6}\right]^2 \times 10^{-3}$$

$$= (55) - 1.677 \left[\frac{(37)(30)(5a)(46)}{(22)(52)\,10^{6}}\right] 10^{-3}$$

(57) b_{tm} STATOR TOOTH WIDTH 1/2 way down tooth in inches -

For slots type (a), (b), (d) and (e), Figure I

$$b_{tm} = \frac{\pi\left[(d) + (h_s)\right]}{(Q)} - (b_s) = \frac{\pi\left[(11) + (22)\right]}{(23)} - (22)$$

For slot type (c), Figure I

$$b_{tm} = \frac{\pi\left[(d) + 2(h_s)\right]}{(Q)} - (b_3) = \frac{\pi\left[(11) + 2(22)\right]}{(23)} - (22)$$

(57a) $b_{t\,1/3}$ STATOR TOOTH WIDTH 1/3 distance up from narrowest section

For slots type (a), (b) and (e)

$$b_{t\,1/3} = (\tau_{s\,1/3}) - (b_s) = (27) - (22)$$

For slot type (c)

$$b_{t\,1/3} = b_{tm} = (57)$$

For slot type (d)

$$b_{t\,1/3} = (\tau_{1/3}) - \frac{2\sqrt{2}}{3}(b_s) = (27) - .94\,(22)$$

(58) b_t TOOTH WIDTH AT STATOR I.D. in inches -

For partially closed slot

$$b_t = \frac{\pi(d)}{(Q)} - b_0 = \frac{\pi(11)}{(23)} - (22)$$

For open slot

$$b_t = \frac{\pi(d)}{(Q)} - b_s = \frac{\pi(11)}{(23)} - (22)$$

(59)	g_{min}	MINIMUM AIR GAP in inches - For concentric pole face $g_{min} = g_{max}$. For non concentric pole face g_{min} = gap at the center of the pole.
(59a)	g_{max}	MAXIMUM AIR GAP in inches
(60)	C_X	REDUCTION FACTOR - Used in calculating conductor permeance and is dependent on the pitch and distribution factor. This factor can be obtained from Graph 1 with an assumed K_d of .955 or calculated as shown $C_X = \frac{(K_X)}{(K_p)^2 (K_d)^2} = \frac{(61)}{(44)^2 (43)^2}$ NOTE: See special case for (e) slot refered to calculation (62)
(61)	K_X	FACTOR TO ACCOUNT FOR DIFFERENCE in phase current in coil sides in same slot $K_X = \frac{1}{4}\left[\frac{3(Y)}{(m)(q)} + 1\right]$ For 3 phase $= \frac{1}{4}\left[\frac{3(31)}{(5)(25)} + 1\right]$ $K_X = \frac{(Y)}{(m)(q)}$ For 2 phase $= \frac{(31)}{(5)(25)}$ NOTE: See special case for (e) slot. Refer to calculation (62)
(62)	λ_i	CONDUCTOR PERMEANCE - The specific permeance for the portion of the stator current that is embedded in the iron. This permeance depends upon the configuration of the slot.

(a) For open slots

$$\lambda_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)}\right]$$

$$\lambda_i = (60)\frac{20}{(5)(25)}\left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)}\right]$$

(b) For partially closed slots with constant slot width

$$\lambda_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o)+(b_s)} + \frac{(h_w)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)}\right]$$

$$\lambda_i = (60)\frac{20}{(5)(25)}\left[\frac{(22)}{(22)} + \frac{2(22)}{(22)+(22)} + \frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)}\right]$$

(d) For round slots

$$\lambda_i = (C_X)\frac{20}{(m)(q)}\left[.62 + \frac{(h_o)}{(b_o)}\right]$$

$$\lambda_i = (60)\frac{20}{(5)(25)}\left[.62 + \frac{(22)}{(22)}\right]$$

(e) For open slots with a winding of one conductor per slot

$$\lambda_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + .6 + \frac{(g)}{2(\tau_s)} + \frac{(\tau_s)}{4(g)}\right]$$

$$\lambda_i = (60)\frac{20}{(5)(25)}\left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + .6 + \frac{(59)}{2(26)} + \frac{(26)}{4(59)}\right]$$

$$\left((C_X) = \frac{1}{(K_p^2)(K_d^2)}\right)$$

$$(K_X) = 1$$

(63) K_E — <u>**LEAKAGE REACTIVE FACTOR**</u> for end turn

$$K_E = \frac{\text{Calculated value } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}} \quad \text{(For machines where (11)} > 8'')$$

where L_E = (48) and abscisa of Graph 1 = $(\gamma)(\tau_s)$ = (31)(26)

$$K_E = \sqrt{\frac{\text{Calculated value of } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}}} \quad \text{(For machines where (11)} < 8'')$$

(64) λ_E — <u>**END WINDING PERMEANCE**</u> - The specific permeance for the end extension portion of the stator winding

$$\lambda_E = \frac{6.28(K_E)}{(\ell)(K_d)^2}\left[\frac{\phi_E L_E}{2n}\right] = \frac{6.28(63)}{(13)(43)^2}\left[\frac{Q_E L_E}{2n}\right]$$

The term $\left[\frac{\phi_E L_E}{2n}\right]$ is obtained from Graph 1.

The symbols used in this (term) do not apply to those of this design manual. Reference information for the symbol origin is included on Graph 1.

(65) -- — <u>**WEIGHT OF COPPER**</u> - The weight of stator copper in lbs.

$$\text{\#'s copper} = .321(n_s)(Q)(a_c)(\ \ _t) = .321(30)(23)(46)(49)$$

(66) -- — <u>**WEIGHT OF STATOR IRON**</u> - in lbs.

$$\text{\#'s iron} = .283\left\{(b_{tm})(Q)(\ell_s)(h_s) + \pi\left[(D) - (h_c)\right](h_c)(\ell_s)\right\}$$

$$.283\left\{(57)(23)(17)(22) + \pi\left[(12) - (24)\right](24)(17)\right\}$$

(67) K_s — <u>**CARTER COEFFICIENT**</u>

$$K_s = \frac{(\tau_s)\left[5(g) + (b_s)\right]}{(\tau_s)\left[5(g) + (b_s)\right] - (b_s)^2} \quad \text{(For open slots)}$$

$$K_s = \frac{(26)\left[5(59) + (22)\right]}{(26)\left[5(59) + (22)\right] - (22)^2}$$

$$K_s = \frac{\tau_s\left[4.44(g) + .75(b_o)\right]}{\tau_s\left[4.44(g) + .75(b_o)\right] - (b_o)^2}$$ (For partially closed slots)

$$K_s = \frac{(26)\left[4.44(59) + .75(22)\right]}{(26)\left[4.44(59) + .75(22)\right] - (22)^2}$$

(68) | -- | AIR GAP AREA - The area of the gap surface at the stator bore

Gap Area = $\pi(d)(\ell) = \pi(11)(13)$

(69) | g_e | EFFECTIVE AIR GAP

$$g_e = (K_s)(g) = (67)(59)$$

(70) | λ_a | AIR GAP PERMEANCE - The specific permeance of the air gap

$$\lambda_a = \frac{6.38(d)}{(P)(g_e)} = \frac{6.38(11)}{(6)(69)}$$

(71) | C_1 | THE RATIO OF MAXIMUM FUNDAMENTAL of the field form to the actual maximum of the field form - This term can be an input or output. For C_1 to be output insert 0. on input sheet. For C_1 to be input, determine C_1 as follows:

For pole heads with only one radius, C_1 is obtained from curve #4. The abscisa is "pole embrace" (α) = (77). The graphical flux plotting method of determining C_1 is explained in the section titled "Derivations" in the Appendix.

(72) C_W **WINDING CONSTANT** - The ratio of the RMS line voltage for a full pitched winding to that which would be introduced in all the conductors in series if the density were uniform and equal to the maximum value. This value can be an input or output. For C_W to be an output, insert 0. on input sheet. For C_W to be an input, calculate as follows:

$$C_W = \frac{(E)(C_1)(K_d)}{\sqrt{2}\,(E_{PH})(m)} = \frac{(3)(71)(43)}{\sqrt{2}\,(4)(5)}$$

Assuming $K_d = .955$, then $C_W = .225\ C_1$ for three phase delta machines and $C_W = .390\ C_1$ for three phase star machines.

(73) C_P **POLE CONSTANT** - The ratio of the average to the maximum value of the field form. This ratio can be an input or output. For C_P to be an output, insert 0. on input sheet. For C_P to be an input, determine as follows:

For pole heads with more than one radius C_P is calculated from the same field form that was used to determine C_1, and this method is described in the section titled "Derivations" in the Appendix. For pole heads with only one radius C_P is obtained from curve #4. Note the correction factor at the top of the curve.

(74) C_M **DEMAGNETIZING FACTOR** - direct axis - This factor can be an input or output. For C_M to be an output, insert 0. on input sheet. For C_M to be an input, determine as follows:

$$C_M = \frac{(\alpha)\pi + \sin[(\alpha)\pi]}{4\sin[(\alpha)\ \pi/2]} = \frac{(77)\pi + \sin[(77)\pi]}{4\sin[(77)\ \pi/2]}$$

C_M can also be obtained from curve 9.

(75) | C_q | **CROSS MAGNETIZING FACTOR** - quadrature axis - This factor can be an input or output. For C_q to be an output, insert 0. on input sheet. For C_q to be an input, determine as follows:

$$C_q = \frac{1/2\cos[(\alpha)\ \pi/2] + (\alpha)\pi - \sin[(\alpha)\pi]}{4\sin[(\alpha)\ \pi/2]}$$

$$= \frac{1/2\cos[(77)\ \pi/2] + (77)\pi - \sin[(77)\pi]}{4\sin[(77)\ \pi/2]}$$

VALID FOR CONCENTRIC POLES.

C_q can also be obtained from curve 9.

(76) | -- | **POLE DIMENSIONS LOCATIONS** per Figure 2

Where:

b_h = width of pole head
b_p = width of pole body
h_h = height of pole head at center
h_f = height of pole body
ℓ_p = length of pole body
ℓ_n = length of pole head

all dimensions in inches

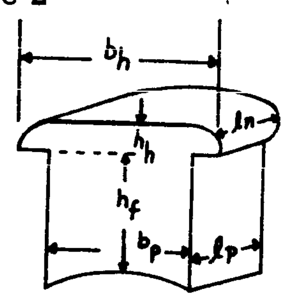


Fig. 2

(77) | α | **POLE EMBRACE**

$$\alpha = \frac{b_h}{\tau_p} = \frac{(76)}{(41)}$$

(78) | A | **AMPERE CONDUCTORS** per inch - The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. Its value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones.

$$A = \frac{(I_{PH})(n_s)(K_P)}{(C)(\tau_s)} = \frac{(8)(30)(44)}{(32)(26)}$$

(79) | X | REACTANCE FACTOR - The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance. It is the percent reactance for unit specific permeance, or the percent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current. Specific permeance is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100(A)(K_d)}{\sqrt{2}\,(C_1)(B_g) \times 10^3} = \frac{100\,(78)(43)}{\sqrt{2}\,(71)(125) \times 10^3}$$

(80) | X_ℓ | LEAKAGE REACTANCE - The leakage reactance of the stator for steady state conditions. When (5) = 3, calculate as follows:

$$X_\ell = X\left[(\lambda_i) + (\lambda_E)\right] = (79)\left[(62) + (64)\right]$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines. When (5) = 2, calculate as follows:

$$\lambda_B = \frac{0.1(d)}{(P)(g_e)}\left[\frac{\sin\left[\frac{3(y)}{(m)(q)}\right]90^o}{(K_P)}\right] = \frac{0.1(11)}{(6)(69)}\left[\frac{\sin\left[\frac{3(31)}{(5)(25)}\right]90^o}{(44)}\right]$$

$X_\ell = X\left[(\lambda_i) + (\lambda_E) + (\lambda_B)\right]$ where λ_B = 0 for 3 phase machines.

X_ℓ = (79)[(62) +)64) + (80)]

(81)	X_{ad}	REACTANCE - direct axis - This is the fictitious reactance due to armature reaction in the direct axis. $X_{ad} = (X)(\lambda_a)(C_1)(C_M)$ = (79)(70)(71)(74)
(82)	X_{aq}	REACTANCE - quadrature axis - This is the fictitious reactance due to armature reaction in the direct axis. $X_{aq} = (X)(C_q)(\lambda_a)$ = (79)(75)(70)
(83)	X_d	SYNCHRONOUS REACTANCE - direct axis - The steady state short circuit reactance in the direct axis. $X_d = (X_\ell) + (X_{ad})$ = (80) + (81)
(84)	X_q	SYNCHRONOUS REACTANCE - quadrature axis - The steady state short circuit reactance in the quadrature axis. $X_q = (X_\ell) + (X_{aq})$ = (80) + (82)
(85)	a_p	POLE AREA - The effective cross sectional area of the pole. $a_p = (b_p)(\ell_p)(K_i)$ = (76)(76)(16)

(86) $\lambda_{e\ell}$ **POLE END LEAKAGE PERMEANCE**

$$\lambda_{e\ell} = \left\{ \frac{2\left[(\ell_n) - (\ell)\right] + (h_f) = .25(b_p)}{\ell} \right\}$$

$$= \left\{ \frac{2\left[(76) - (13)\right] + (76) + .25(76)}{(13)} \right\}$$

(87) $\lambda_{t\ell}$ **POLE TIP LEAKAGE PERMEANCE**

$$\lambda_{t\ell} = \left\{ \frac{2\left[(h_h) + (g) - (\tau_p)/18\right]}{(\tau_p) - (b_h)} \right\}$$

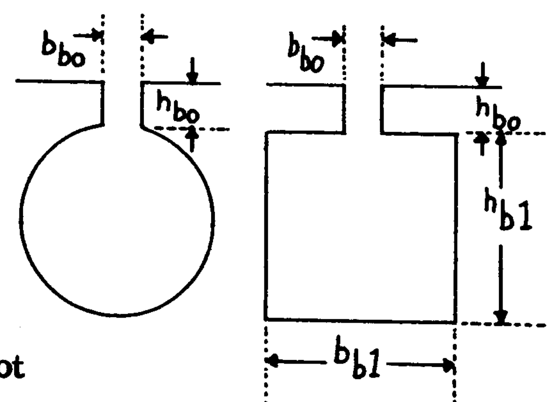
$$= \left\{ \frac{2\left[(76) + (59) - (41)/18\right]}{(41) - (76)} \right\}$$

(88) $\lambda_{s\ell}$ **POLE SIDE LEAKAGE PERMEANCE**

$$s = \left\{ \frac{(h_f)}{\pi/(P)\left[(d_r) - 2(h_h) - .5(h_f)\right] - (b_p)} \right\}$$

$$= \left\{ \frac{(76)}{\pi/(6)\left[(11a) - 2(76) - .5(76)\right] - (76)} \right\}$$

(89) -- **DAMPER SLOT DIMENSIONS**



b_{bo} - width of slot opening

h_{bo} - height of slot opening

h_b - diameter of round slot

h_{b1} - height of bar section of slot

b_{b1} - width of rectangular slot

(90)	--	<u>DAMPER BAR DIA OR WIDTH</u> in inches
(91)	h_{b1}	<u>DAMPER BAR THICKNESS</u> in inches - Damper bar thickness considered equal to damper bar slot height (h_b) per item (89). Set this item = 0 for round bar.
(92)	n_b	<u>NUMBER OF DAMPER BARS PER POLE</u>
(93)	ℓ_b	<u>DAMPER BAR LENGTH</u> in inches
(94)	τ_b	<u>DAMPER BAR PITCH</u> in inches
(95)	ρ_D	<u>RESISTIVITY</u> of damper bar @ 20°C in ohm-inches - Refer to table given in item (51) for conversion factors.
(96)	$X_D\,^\circ C$	<u>DAMPER BAR TEMP $^\circ C$</u> - Input temp at which damper losses are to be calculated.
(97)	ρ_D (hot)	RESISTIVITY of damper bar @ $X_D\,^\circ C$ $\rho_{D(hot)} = (\rho_D)\left[\frac{(X_D\,^\circ C) + 234.5}{254.5}\right] = (95)\left[\frac{(96) + 234.5}{254.5}\right]$

(98)	a_{cd}	<u>CONDUCTOR AREA OF DAMPER BAR</u> - Calculate same as stator conductor area
		 At (46) except substitute $\begin{cases} (91) \text{ for } (39) \\ (90) \text{ for } (33) \end{cases}$
		 If (91) = 0
		 $a_{cd} = .25\pi\,(\text{damper bar dia})^2 = .25\pi(90)^2$
		 If (91) $\neq$ 0
		 $a_{cd} = (h_{b1})\,(\text{damper bar width}) = (91)(90)$

(98a)	V_r	PERIPHERAL SPEED - The velocity of the rotor surface in feet per minute $V_r = \frac{\pi(d_r)(RPM)}{12} = \frac{\pi(11a)(7)}{12}$
(99)	N_P	NUMBER OF FIELD TURNS PER POLE
(100)	ℓ_{tr}	MEAN LENGTH OF FIELD TURN
(101)	--	FIELD CONDUCTOR DIA OR WIDTH in inches
(102)	--	FIELD CONDUCTOR THICKNESS in inches - Set this item = 0. for round conductor
(103)	$X_f{}^oC$	FIELD TEMP IN ^oC - Input temp at which full load field loss is to be calculated.
(104)	ρ_f	RESISTIVITY of rotor field conductor @ 20^oC in micro ohm-inches. Refer to table given in item (51) for conversion factors.
(105)	ρ_f (hot)	RESISTIVITY of rotor field conductor at $X_f{}^oC$ $\rho_{f\ (hot)} = \rho_f \left[\frac{(X_f{}^oC) + 234.5}{254.5}\right] = (104) \left[\frac{(103) + 234.5}{254.5}\right]$
(106)	a_{cf}	CONDUCTOR AREA OF ROTOR FIELD WDG - Calculate same as stator conductor area (46) except substitute $\begin{cases} (102) \text{ for } (39) \\ (101) \text{ for } (33) \end{cases}$
(107)	R_f (cold)	COLD FIELD RESISTANCE @ 20^oC $R_{f\ (cold)} = (\rho_f) \frac{(N_P)(P)(\ell_{tr})}{(a_{cf})} = (104) \frac{(99)(6)(100)}{(106)}$

(108)	R_f (hot)	**HOT FIELD RESISTANCE** - Calculated at X_f °C (103) $R_{f\,(hot)} = (\rho_{f\,hot}) \frac{(N_p)(P)(\ell_{tr})}{(a_{cf})} = (105)\frac{(99)(6)(100)}{(106)}$
(108a)	--	**WEIGHT OF ROTOR FIELD COPPER** in lbs $\#'s \text{ of copper} = .321(N_p)(P)(\ell_{tr})(a_{cf})$ $= .321(99)(6)(100)(106)$
(108b)	--	**WEIGHT OF ROTOR IRON** - Because of the large number of different pole shapes, one standard formula cannot be used for calculating rotor iron weight. Therefore the computer will not calculate rotor iron weight. The space is allowed on the input sheet for record purposes only. By inserting 0. in the space allowed for rotor iron weight, the computer will show "0." on the output sheet. If the rotor iron weight is available and inserted on input sheet, then the output sheet will show this same weight on the output sheet.
(109)	λ_b	**PERMEANCE OF DAMPER BAR** - The permeance of that portion of the damper bar that is embedded in pole iron. For round slot $\lambda_b = 6.38\left[\frac{(h_{bo})}{(b_{bo})} + .62 + .5\right] = 6.38\left[\frac{(89)}{(89)} + .62 + .5\right]$ For rectangular slot $\lambda_b = 6.38\left[\frac{(h_{bo})}{(b_{bo})} + \frac{(h_{b1})}{3(b_{b1})} + .5\right] = 6.38\left[\frac{(89)}{(89)} + \frac{(89)}{3(89)} + .5\right]$

(110)	λ_{pt}	**PERMEANCE OF END PORTION OF DAMPER BARS**

$$\lambda_{pt} = 6.38 \left\{ \frac{(b_h) - (\tau_b)\left[(n_b) - 1\right]}{3(g_e)} \right\}$$

$$= 6.38 \left\{ \frac{(76) - (94)\left[(92) - 1\right]}{3(69)} \right\}$$

(111)	λ_F	**ROTOR LEAKAGE PERMEANCE**

$$\lambda_F = 4.25\left[(\lambda_s) + 1.5(\lambda_{t\ell})\right] + 6.38(\lambda_{e\ell})$$

$$= 4.25\left[(88) + 1.5(87)\right] + 6.38(86)$$

(112)	X_F	**FIELD LEAKAGE REACTANCE**

$$X_F = (X_{ad})\left[1 - \frac{\left[(C_1)/(C_m)\right]}{2(C_p) + \frac{4(\lambda F)}{\pi(\lambda_a)}}\right]$$

$$= (81)\left[1 - \frac{\left[(71)/(74)\right]}{2(73) + \frac{4(111)}{\pi(70)}}\right]$$

(113)	L_f	**FIELD SELF INDUCTANCE**

$$L_f = (N_P)^2(P)(\ell_P)\left[(C_P)(\lambda_a)\frac{\pi}{2} + (\lambda_f)\right] \times 10^{-8}$$

$$= (99)^2(6)(76)\left[(73)(70)\frac{\pi}{2} + (111)\right] \times 10^{-8}$$

(114) λ_{Dd} **PERMEANCE OF DAMPER BAR** - in direct axis

$$\lambda_{Dd} = \left\{\cos\left[\frac{\{(n_b) - 1\}(\tau_b)\pi}{2(\tau_P)}\right]\right\}\left\{\frac{\{(\lambda_b) + (\lambda_{Pt})\}(\lambda_F)}{\lambda_b + \lambda_{Pt} + \lambda_F}\right\}$$

$$= \left\{\cos\left[\frac{\{(92) - 1\}(94)}{2(94)}\right]\right\}\left\{\frac{\{(109) + (110)\}(111)}{(109) + (110)\ (111)}\right\}$$

(115) X_{Dd} **DAMPER LEAKAGE REACTANCE** - in direct axis

$$X_{Dd} = X(\lambda_{Dd}) = (79)(114)$$

(116) λ_{Dq} **PERMEANCE IN QUADRATURE AXIS**

For round slot

$$\lambda_{D_q} = \frac{20(\tau_b)}{(\tau_P)}\left[\frac{(h_{bo})}{(b_{bo})} + .62 + .5 + \frac{(g)}{(\tau_b)}\right]$$

$$= \frac{20(94)}{(41)}\left[\frac{(89)}{(89)} + .62 + .5 + \frac{(59)}{(94)}\right]$$

For rectangular slot

$$\lambda_{(Dq)} = \frac{20(\tau_b)}{(\tau_P)}\left[\frac{(h_{bo})}{(b_{bo})} + \frac{(h_{b1})}{3(b_{b1})} + .5 + \frac{(g)}{(\tau_b)}\right]$$

$$= \frac{20(94)}{(41)}\left[\frac{(89)}{(89)} + \frac{(89)}{3(89)} + .5 + \frac{(59)}{(94)}\right]$$

(117) X_{Dq} **DAMPER LEAKAGE REACTANCE** - in quadrature axis

$$X_{Dq} = X(\lambda_{Dq}) = (79)(116)$$

(118) X'_{du} **UNSATURATED TRANSIENT REACTANCE**

$$X'_{du} = (X_\ell) + (X_f) = (80) + (112)$$

(119)	X_d'	<u>SATURATED TRANSIENT REACTANCE</u> $X_d' = .88(X_{du}') = .88(118)$
(120)	X_d''	<u>SUBTRANSIENT REACTANCE</u> in direct axis When damper bars exist, i.e. when $(92) \neq 0$ $X_d'' = (X_\ell) + (X_{Dd}) = (80) + (115)$ When no damper bars exist, i.e. when $(92) = 0$ $X_d'' = (X_d') = (119)$
(121)	X_q''	<u>SUBTRANSIENT REACTANCE</u> in quadrature axis When damper bar exists, i.e. when $(92) \neq 0$ $X_q'' = (X_\ell) + (X_{Dq}) = (80) + (116)$ When no damper bars exist, i.e. when $(92) = 0$ $X_q'' = X_q = (84)$
(122)	X_2	<u>NEGATIVE SEQUENCE REACTANCE</u> - The reactance due to the field which rotates at synchronous speed in a direction opposite to that of the rotor. $X_2 = .5\left[X_d'' + X_q''\right] = .5\left[(120) + (121)\right]$
(123)	X_0	<u>ZERO SEQUENCE REACTANCE</u> - The reactance drop across any one phase (star connected) for unit current in each of the phases. The machine must be star connected for otherwise no zero sequence current can flow and the term then has no significance.

If (28) = 0 Then $X_o = 0$

If (28) $\neq$ 0 Then

$$X_o = X\left\{\frac{(K_{xo})}{(K_{x1})}\left[(\lambda_i) + (\lambda_{Bo})\right] + \frac{1.667\left[(h_1) + 3(h_3)\right]}{(m)(q)(K_p)^2(K_d)^2(b_s)} + .2(\lambda_E)\right\}$$

$$= (79)\left\{\frac{(123a)}{(123b)}\left[(62) + (123c)\right] + \frac{1.667\left[(22) + 3(22)\right]}{(5)(25)(44)^2(43)^2(22)} + .2(64)\right\}$$

(123a) K_{xo}

If (30) = 1 Then $K_{xo} = 1$

If (30) $\neq$ 1 Then $K_{xo} = \frac{3(\gamma)}{(m)(q)} - 2$

$$= \frac{3(31)}{(5)(25)} - 2$$

(123b) K_{x1}

If (30) = 1 Then $K_{x1} = 1$

If (30) $\neq$ 1 Then:

$$K_{x1} = \left[\frac{3(\gamma)}{4(m)(q)} + \frac{1}{4}\right] = \left[\frac{3(31)}{4(5)(25)} + \frac{1}{4}\right] \quad \text{If } (31a) \geq .667$$

$$K_{x1} = \left[\frac{3(\gamma)}{4(m)(q)} - \frac{1}{4}\right] = \left[\frac{3(31)}{4(5)(25)} - \frac{1}{4}\right] \quad \text{If } (31a) < .667$$

(123c) λ_{Bo}

If (92) = 0 Then:

$$\lambda_{Bo} = \frac{(K_{xo})}{(K_p)^2}\left[.07(\lambda_a)\right] = \frac{(123a)}{(44)^2}\left[.07(70)\right]$$

If (92) $\neq$ 0 Then

$$\lambda_{Bo} = \frac{\frac{(K_{xo})}{(K_{x1})}(\lambda_{Dq}) + \frac{(K_{xo})}{(K_p)^2}\left[.07(\lambda_a)\right]}{\left\{\frac{(K_{xo})}{(K_{x1})}(\lambda_{Dq})\right\}\left\{\frac{(K_{xo})}{(K_p)^2}\left[.07(\lambda_a)\right]\right\}}$$

$$= \frac{\frac{(123a)}{(123b)}(116) + \frac{(123a)}{(44)^2}\left[.07(70)\right]}{\left\{\frac{(123a)}{(123b)}(116)\right\}\left\{\frac{(123a)}{(44)^2}\left[.07(70)\right]\right\}}$$

(124)	ϕ_T	<u>TOTAL FLUX IN KILO LINES</u> $$\phi_T = \frac{6(E)10^6}{(C_W)(n_e)(RPM)} = \frac{6(3)10^6}{(72)(45)(17)}$$
(125)	B_g	<u>GAP DENSITY</u> in Kilo Lines/in^2 - The maximum flux density in the air gap $$B_g = \frac{(\phi_T)}{\pi(d)(\ell)} = \frac{(124)}{\pi(11)(13)}$$
(126)	ϕ_P	<u>FLUX PER POLE</u> in Kilo Lines $$\phi_P = \frac{(\phi_T)(C_P)}{(P)} = \frac{(124)(73)}{(6)}$$
(127)	B_t	<u>TOOTH DENSITY</u> in Kilo Lines/in^2 - The flux density in the stator tooth at 1/3 of the distance from the minimum section. $$B_t = \frac{\phi_T}{(Q)(\ell_s)(b_{t\,1/3})} = \frac{(124)}{(23)(17)(57a)}$$
(128)	B_c	<u>CORE DENSITY</u> in Kilo Lines/in^2 - The flux density in the stator core $$B_c = \frac{(\phi_P)}{2(h_c)(\ell_s)} = \frac{(126)}{2(24)(17)}$$

(129) F_T — **STATOR TOOTH AMPERE TURNS**

$$F_T = h_s \left[\text{NI/in at density } B_t \right]$$

$$= (22) \left[\begin{array}{l} \text{Look-up on stator magnetization curve given in} \\ \text{(18) @ density (127)} \end{array} \right]$$

(130) F_c — **STATOR CORE AMPERE TURNS**

$$F_c = \left[\frac{\pi \left[(D) - (h_c) \right]}{4(P)} \right] \left[\text{NI/in @ density of } B_c \right]$$

$$= \left[\frac{\pi \left[(12) - (24) \right]}{4(6)} \right] \left[\begin{array}{l} \text{Look-up on stator magnetization curve} \\ \text{given in (18) @ density (128)} \end{array} \right]$$

(130a) F_s — **STATOR AMPERE TURNS**, total

$$F_s = (F_T) + (F_c) = (129) + (130)$$

(131) F_g — **AIR GAP AMPERE TURNS** - The field ampere turns per pole required to force flux across the air gap when operating at no load with rated voltage.

$$F_g = \frac{(B_g)(g_e)}{3.19} = \frac{(125)(69)}{3.19}$$

(132) T'_{do} — **OPEN CIRCUIT TIME CONSTANT** - The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit. Field resistance at room temperature (20°C) is used in this calculation.

$$T'_{do} = \frac{L_F}{R_F} = \frac{(113)}{(107)}$$

(133)	T_a	**ARMATURE TIME CONSTANT** - Time constant of the D.C. component. In this calculation stator resistance at room temperature ($20^{o}C$) is used.

$$T_a = \frac{X_2}{200\pi(f)(r_a)} = \frac{(122)}{200\pi(5a)(133)}$$

$$\text{where } r_a = \frac{(m)(I_{PH})^2(R_{SPH\,cold})}{\text{Rated KVA}} = \frac{(5)(8)^2(53)}{(2)}$$

(134)	T'_d	TRANSIENT TIME CONSTANT - The time constant of the transient reactance component of the alternating wave.

$$T'_d = \frac{(X'_d)}{(X_d)}(T'_{do}) = \frac{(119)}{(83)}(132)$$

(135)	T''_d	SUBTRANSIENT TIME CONSTANT - The time constant of the subtransient component of the alternating wave. This value has been determined empirically from tests on large machines. Use following values.

T''_d = .035 second at 60 cycle

T''_d = .005 second at 400 cycle

(136)	F_{SC}	SHORT CIRCUIT AMPERE TURNS - The field ampere turns required to circulate rated stator current when the stator is short circuited.

$$F_{SC} = (X_d)(F_g) = (83)(131)$$

(137)	SCR	SHORT CIRCUIT RATIO - The ratio of the field current to produce rated voltage on open circuit to the field current required to produce rated current on short circuit.

Since the voltage regulation depends on the leakage reactance and the armature reaction, it is closely related to the current which the machine produces under short circuit conditions, and therefore is directly related to the SCR.

$$SCR = \frac{F_{NL}}{F_{SC}} = \frac{(142)}{(136)}$$

The items to follow (138) to (158) are to be calculated for variable loads. The first set of calculations are at no load. These calculations will then be repeated for 100% load. From then on any variation in load would be a repeat of the 100% load calculations with the proper percent load inserted.

(138) ϕ_ℓ **LEAKAGE FLUX** - at no load

$$\phi_\ell = .00638\left[(\lambda_{s\ell}) + (\lambda_{e\ell}) + (\lambda_{t\ell})\right]\left[(F_g) + (F_S)\right](\ell_P)$$

$$= .00638\left[(88) + (86) + (87)\right]\left[(131) + (130a)\right](76)$$

(139) ϕ_{PT} **TOTAL FLUX PER POLE - at no load**

$$\phi_{PT} = \phi_P + \phi_\ell = (126) + (138)$$

(140) B_P **POLE DENSITY** - The apparent flux density at the base of the pole. Note that no provision is made in this manual for calculating the density in the spider section. It is therefore important to remember not to restrict the flux area through this section.

$$B_P = \frac{(\phi_{PT})}{(a_P)} = \frac{(139)}{(85)}$$

(141) F_P **POLE AMPERE TURNS** - at no load. The ampere turns per pole required to force the flux through the pole and spider at no load rated voltage. In general the spider density is kept fairly low and its ampere turns can be neglected. The no load pole ampere turns per pole are calculated as the product of $(h_f) + (h_h)$ times the NI per inch at the density (B_P). Use magnetization curve submitted per item (18) for rotor.

$$F_P = \left[(h_f) + (h_h)\right]\left[\text{NI/in @ density } (B_P)\right]$$

$$= \left[(76) + (76)\right]\left[\begin{array}{l}\text{Look-up on rotor magnetization} \\ \text{curve given in (18) @ density (140)}\end{array}\right]$$

(142) F_{NL} **TOTAL AMPERE TURNS** - at no load. The total ampere turns per pole required to produce rated voltage at no load.

$$F_{NL} = \left[(F_g) + (F_S) + (F_P)\right] = \left[(131) + (130a) + (141)\right]$$

(143) I_{FNL} **FIELD CURRENT - at no load**

$$I_{FNL} = (F_{NL})/(N_P) = (142)/(99)$$

(144) S_F **CURRENT DENSITY** - at no load. Amperes per square inch of field conductor.

$$S_F = (I_{FNL})/(a_{cf}) = (143)/(106)$$

(145)	E_F	**FIELD VOLTS** - at no load. This calculation is made with cold field resistance at 20°C for no load condition. $$E_F = (I_{FNL})(R_{f\,cold}) = (143)(107)$$
(146)	I^2R_R	**ROTOR I^2R** - at no load. The copper loss in the field winding is calculated with cold field resistance at 20°C for no load condition. $$\text{Rotor } I^2R = (I_{FNL})^2 (R_{f\,cold}) = (143)^2 (107)$$
(147)	F & W	**FRICTION & WINDAGE LOSS** - There is no known calculation method that will give accurate results for this loss. The best results are obtained by using existing data. For ratioing purposes, the loss can be assumed to vary approximately as the 5/2 power of the rotor diameter and as the 3/2 power of the RPM. When no existing data is available, the following calculation can be used for an approximate answer. Insert 0. when computer is to calculate F & W. Insert actual F & W when available. Use same value for all load conditions. $$F \& W = 2.52 \times 10^{-6} (d_r)^{2.5} (\ell_h) (RPM)^{1.5}$$ $$= 2.52 \times 10^{-6} (11a)^{2.5} (76) (7)^{1.5}$$
(148)	W_{TNL}	**STATOR TEETH LOSS** - at no load. The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density.

$$W_{TNL} = .453(b_{t\,1/3})(Q)(\ell_s)(h_s)(K_Q)$$

$$= .453(57a)(23)(17)(22)(148)$$

$$\text{Where } K_Q = (k)\left[\frac{(B_t)}{(B)}\right]^2 = (19)\left[\frac{(127)}{(20)}\right]^2$$

(149) W_c **STATOR CORE LOSS** - The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density (B_c).

$$W_c = 1.42\left[(D) - (h_c)\right](h_c)(\ell_s)(K_Q)$$

$$= 1.42\left[(12) - (24)\right](24)(17)(149)$$

$$\text{Where } K_Q = (k)\left[\frac{(B_c)}{(B)}\right]^2 = (19)\left[\frac{(128)}{(20)}\right]^2$$

(150) W_{NPL} **POLE FACE LOSS** - at no load. The pole surface losses are due to slot ripple caused by the stator slots. They depend upon the width of the stator slot opening, the air gap, and the stator slot ripple frequency. The no load pole face loss (W_{PNL}) can be obtained from Graph 2. Graph 2 is plotted on the bases of open slots. In order to apply this curve to partially open slots, substitute b_o for b_s. For a better understanding of Graph 2, use the following sample.

K_1 as given on Graph 2 is derived empirically and depends on lamination material and thickness. Those values given on Graph 2 have been used with success. K_1 is an input and must be specified. See item (151) for values of K_1.

(150) (Cont.)

K_2 is shown as being plotted as a function of $(B_G)^{2.5}$. Also note that upper scale is to be used. Another note in the lower right hand corner of graph indicates that for a solid line (——), the factor is read from the left scale, and for a broken or dashed line (—— - —— -), the right scale should be read. For example, find K_2 when B_G = 30 kilo lines. First locate 30 on upper scale. Read down to the intersection of solid line plot of $K_2 = f(B_G)^{2.5}$. At this intersection read the left scale for K_2. $K_2 = .28$. Also refer to item (152) for K_2 calculations.

K_3 is shown as a solid line plot as a function of $(F_{SLT})^{1.65}$. The note on this plot indicates that the upper scale X 10 should be used. Note F_{SLT} = slot frequency. For an example, find K_3 when F_{SLT} = 1000. Use upper scale X 10 to locate 1000. Read down to intersection of solid line plot of $K_3 = f(F_{SLT})^{1.65}$. At this intersection read the left scale for K_3. $K_3 = 1.35$. Also refer to item (153) for K_3 calculations.

For K_4 use same procedure as outlined above except use lower scale. Do not confuse the dashed line in this plot with the note to use the right scale. The note does not apply in this case. Read left scale. Also refer to item (154) for K_4 calculations.

For K_5 use bottom scale and substitute b_o for b_s when using partially closed slot. Read left scale when using solid plot. Use right scale when using dashed plot. Also refer to item (155) for K_5 calculations.

(150) (Cont.)

For K_6 use the scale attached for C_1 and read K_6 from left scale. Also refer to item (156) for K_6 calculations.

The above factors (K_2), (K_3), (K_4), (K_5), (K_6) can also be calculated as shown in (152), (153), (154), (155), (156), respectively.

$$W_{PNL} = \pi(d)(\ell)(K_1)(K_2)(K_3)(K_4)(K_5)(K_6)$$
$$= \pi(11)(13)(151)(152)(153)(154)(155)(156)$$

(151) K_1

K_1 is derived empirically and depends on lamination material and thickness. The values used successfully for K_1 are shown on Graph 2. They are

K_1 = 1.17 for .028 lam thickness, low carbon steel
= 1.75 for .063 lam thickness, low carbon steel
= 3.5 for .125 lam thickness, low carbon steel
= 7.0 for solid core

K_1 is an input and must be specified on input sheet.

(152) K_2

K_2 can be obtained from Graph 2 (see item 150) for explanation of Graph 2) or it can be calculated as follows:

$$K_2 = f(B_G) = 6.1 \times 10^{-5} (B_G)^{2.5}$$
$$= 6.1 \times 10^{-5} (125)^{2.5}$$

(153) K_3

K_3 can be obtained from Graph 2 (see item 150) for explanation of Graph 2) or it can be calculated as follows:

$$K_3 = f(F_{SLT}) = 1.5147 \times 10^{-5} (F_{SLT})^{1.65}$$
$$= 1.5147 \times 10^{-5} (153)^{1.65}$$

Where $F_{SLT} = \frac{(RPM)}{60} (Q)$

$$= \frac{(7)}{60} (23)$$

(154)	K_4	K_4 can be obtained from Graph 2 (see item (150) for explanation of Graph 2) or it can be calculated as follows: For $\tau_s \leqq .9$ $K_4 = f(\tau_s) = .81(\tau_s)^{1.285}$ $= .81(26)^{1.285}$ For $.9 \leqq \tau_s \leqq 2.0$ $K_4 = f(\tau_s) = .79(\tau_s)^{1.145}$ $= .79(26)^{1.145}$ For $\tau_s > 2.0$ $K_4 = f(\tau_s) = .92(\tau_s)^{.79}$ $= .92(26)^{.79}$
(155)	K_5	K_5 can be obtained from Graph 2 (see item (150) for explanation of Graph 2) or it can be calculated as follows: For $(b_s)/(g) \leqq 1.7$ $K_5 = f(b_s/g) = .3\left[(b_s)/(g)\right]^{2.31}$ $= .3\left[(22)/(59)\right]^{2.31}$ NOTE: For partially open slots substitute b_o for b_s in equations shown. For $1.7 < (b_s)/(g) \leqq 3$ $K_5 = f(b_s)/(g) = .35\left[(b_s)/(g)\right]^2$ $= .35\left[(22)/(59)\right]^2$

For $3 < (b_s)/(g) \leq 5$

$$K_5 = f(b_s)/(g) = .625\left[(b_s)/(g)\right]^{1.4}$$

$$= .625\left[(22)/(59)\right]^{1.4}$$

For $(b_s)/(g) > 5$

$$K_5 = f\left[(b_s)\right]/(g) = 1.38\left[(b_s)/(g)\right]^{.965}$$

$$= 1.38\left[(22)/(59)\right]^{.965}$$

(156) | K_6 | K_6 can be obtained from Graph 2 (see item (150) for explanation of Graph 2) or it can be calculated as follows:

$$K_6 = f(C_1) = 10^{\left[.9323(C_1) - 1.60596\right]}$$

$$= 10^{\left[.9323(71) - 1.60596\right]}$$

(157) | W_{DNL} | <u>DAMPER LOSS</u> - at no load at $20^{o}C$. This loss is produced by slot ripple in the damper winding. At no load this loss is calculated from curves 7 and 8.

$$W_{DNL} = \frac{1.246(P)(n_b)(\ell_b)(\rho_D)}{(a_{cr}) \times 10^3}\left[(\tau_s)(B_g)(K_{P1})(K_g)\right]^2$$

$$\left\{(K_{f1})\left[\frac{K_{W1}}{2(\lambda_s) + \left[(\lambda_g)/(K_{\phi 1})\right]}\right]^2 + (K_{f2})\left[\frac{(K_{W2})}{2(\lambda_s) + \left[(\lambda_g)/(K_{\phi 2})\right]}\right]^2\right\}$$

$$W_{DNL} = \frac{1.246(6)(92)(93)(95)}{(98) \times 10^3}\left[(26)(125)(157)(157)\right]^2$$

$$\left\{(157)\left[\frac{(157)}{2(157) + \left[(157)/(157)\right]}\right]^2 + (157)\left[\frac{(157)}{2(157) + \left[(157)/(157)\right]}\right]^2\right.$$

(157) (Cont.)

Where $K_{P1} = 1 - \frac{1}{\sqrt{1 + \left[(b_s)/2(g)\right]^2}}$

$= 1 - \frac{1}{\sqrt{1 + \left[(22)/2(59)\right]^2}}$

NOTE: Substitute b_o for b_s when partially opened stator slot is used.

K_{P1} can also be obtained from curve 7 where abscissa is $(b_s)/(g)$ or $(b_o)/(g) = (22)/(59)$

Where $K_g = (K_s) = (67)$

Where $g' = (K_g)(g) = (157)(59)$

Where K_{f1} & K_{f2} are obtained from curve 7

Where the abscissa is S_1 or S_2

$$S_1 = 3.2\sqrt{\frac{(f_{S1})}{(D)}} = 3.2\sqrt{\frac{(157)}{(95)}}$$

$$S_2 = 3.2\sqrt{\frac{(f_{S2})}{(D)}} = 3.2\sqrt{\frac{(157)}{(95)}}$$

Where $f_{S1} = 2qmf = 2(25)(5)(5a)$

$f_{S2} = 2(f_{S1})$

Where K_{W1} and K_{W2} are obtained from curve 8. where the abscissa is $(b_s)/(\tau_s)$ for open slots or $(b_o)/(\tau_s)$ for semi-enclosed slots $(b_s)/(\tau_s) = (22)/(26)$

(157)	(Cont.)	Where λ_t is obtained from curve 8 Where the abscissa is $(b_{bo})/(g') = \frac{(89)}{(157)}$ When 91 = 0 or when (90) = (91) $\lambda_C = \frac{.75}{(K_{f1})} = \frac{.75}{(157)}$ For round or square slots When 91 $\neq$ 0 and when (90) $\neq$ (91) $\lambda_C = \frac{(h_{b1})}{3(b_{b1})(K_{f1})} = \frac{(91)}{3(89)(157)}$ Where $\lambda_S = \frac{(h_{bo})}{(b_{bo})} + (\lambda_t) + (\lambda_C)$ $= \frac{(89)}{(89)} + (157) + (157)$ Where $\lambda_g = \frac{\tau_b}{g'} = \frac{(94)}{(157)}$ Where $K_{\phi 1}$ and $K_{\phi 2}$ are obtained from curve 8 Where the abscissa is $(\tau_b)/(\tau_s) = (94)/(26)$
(158)	I^2R	<u>STATOR I^2R</u> - at no load. This item = 0. Refer to item (173) for 100% load stator I^2R.
(158a)	--	<u>EDDY LOSS</u> - at no load. This item = 0. Refer to item (173a) for 100% load eddy loss.
(159)	--	<u>TOTAL LOSSES</u> - at no load. Sum of all losses Total losses = (Rotor I^2R) + (F & W) + (Stator Teeth Loss) + (Stator Core Loss) + (Pole Face Loss) + (Damper Loss) = (146) + (147) + (148) + (149) + (150) + (157)

NOTE: The output sheet shows the next items to be: (Rating), (Rating + Losses), (% Losses), (% Efficiency). These items do not apply to the no load calculation since the rating is zero. Refer to items (175), (176), (177), (178) for these calculations under load.

Item (138) through (159) have been calculated for 0% load or no load. They should all be repeated now for 100% load.

(160)	$\phi_{\ell\ell}$	**<u>LEAKAGE FLUX PER POLE</u> at 100% load**

$$\phi_{\ell\ell} = \phi_{\ell}\left\{\frac{(e_d)(F_g) + \left[1 + \cos(\theta)\right](F_T) + (F_C)}{(F_g) + (F_T) + (F_C)}\right\}$$

$$= (138) \quad \frac{(160a)(131) + \left[1 + \cos(160b)\right](129) + (130)}{(131) + (129) + (130)}$$

(160a)	e_d	Where $e_d = \cos\epsilon + (X_d)\sin\psi$

$$= \cos(160b) + (83)\sin(160b)$$

(160b)	θ	Where $\theta = \cos^{-1}\left[(\text{Power Factor})\right]$

$$= \cos^{-1}\left[(9)\right]$$

Where $\psi = \tan^{-1}\left[\dfrac{\sin(\theta) + (X_q)/(100)}{\cos(\theta)}\right]$

$$= \tan^{-1}\left[\frac{\sin(160b) + (84)/(100)}{\cos(160b)}\right]$$

Where $\epsilon = \psi - \theta = (160b) - (160b)$

(161) ϕ_{PL} **FLUX PER POLE** at 100% load

FOR P.F. 0 TO .95

$$\phi_{PL} = (\phi_P)\left[(e_d) - \frac{.0093(X_{ad})}{100}\sin(\psi)\right]$$

$$= (126)\left[(160a) - \frac{.0093(81)}{100}\sin(160b)\right]$$

FOR P.F. .95 TO 1.0 $\phi_{PL} = (\phi_P)(K_c) = (126)(9a)$

(162) ϕ_{PTL} **TOTAL FLUX PER POLE** at 100% load

$$\phi_{PTL} = \phi_{PL} + \phi_{ll} = (161) + (160)$$

(163) B_{PL} **FLUX DENSITY AT BASE OF POLE** at 100% load

$$B_{PL} = \frac{\phi_{PTL}}{a_P} = \frac{(162)}{(85)}$$

(164) F_{PL} **AMPERE TURNS PER POLE** at 100% load

$$F_{PL} = \left[(h_f) + (h_h)\right]\left[NI/in\ @\ density\ (B_{PL})\right]$$

$$= \left[(76) + (76)\right]$$

Look-up ampere turns/inch on rotor magnetization curve given in (18) at density (163)

(165) F_{FL} **TOTAL AMPERE TURNS PER POLE** at 100% load - The total ampere turns per pole required to produce rated load.

$$F_{FL} = (e_d)(F_g) + \left[1 + \cos(\theta)\right](F_T) + (F_C) + (F_{PL})$$

$$= (160a)(131) + \left[1 + \cos(160b)\right](129) + (130) + (164)$$

(166) I_{FFL} **FIELD CURRENT** at 100% load

$$I_{FFL} = (F_{FL})/(N_P) = (165)/(99)$$

(167) -- **CURRENT DENSITY** at 100% load

$$\text{Current Density} = (I_{FFL})/(a_{cf}) = (166)/(106)$$

(168) E_{FFL} **FIELD VOLTS** at 100% load - This calculation is made with hot field resistance at expected temperation at 100% load.

$$\text{Field Volts} = (I_{FFL})(R_{f\,hot}) = (166)(108)$$

(169) I^2R_R **ROTOR I^2R** at 100% load - The copper loss in the field winding is calculated with hot field resistance at expected temperature for 100% load condition.

$$\text{Rotor } I^2R = (I_{FFL})^2(R_{F\,hot}) = (166)^2(108)$$

(170) W_{TFL} **STATOR TEETH LOSS** at 100% load - The stator tooth loss under load increases over that of no load because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings.

$$W_{TFL} = \left\{ \left[2.27(X_d) \right]^{1.8} \frac{(\%\ \text{Load})}{100} + 1 \right\} (W_{TNL})$$

NOTE (X_d) is in per unit

$$= \left\{ 2.\left[27(83)\right]^{1.8} \quad 1 + 1 \right\} \quad (148)$$

(171) W_{PFL} **POLE FACE LOSS** at 100% load

$$W_{PFL} = \left\{ \left[\frac{(K_{sc})(I_{PH}) \frac{(\%\ \text{Load})}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{PNL})$$

$$= \left\{ \left[\frac{(171)(8)\ 1\ (30)}{(32)(131)} \right]^2 + 1 \right\} (150)$$

(K_{sc}) is obtained from Graph 3

(172) W_{DFL} **DAMPER LOSS** at 100% load

$$W_{DFL} = \left\{ \left[\frac{(K_{sc})(I_{PH}) \frac{(\%\ Load)}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{DNL}) \times \frac{(\ell_{D\,hot})}{(\ell_{D\,cold})}$$

$$= \left\{ \left[\frac{(172)(8)\ 1\ (30)}{(32)(131)} \right]^2 + 1 \right\} (157)\ \frac{(97)}{(95)}$$

(K_{sc}) is obtained from Graph 3

(173) I^2R **STATOR I^2R** at 100% load - The copper loss based on the D.C. resistance of the winding. Calculate at the maximum expected operating temperature.

$$I^2R = (m)(I_{PH})^2\ (R_{SPH\,hot})\ \frac{(\%\ Load)}{100}$$

$$= (5)(8)^2\ (54)\ 1.$$

(173a) -- **EDDY LOSS** - Stator I^2R loss due to skin effect

$$\text{Eddy Loss} = \left[\frac{(EF_{top}) + (EF_{bot})}{2} - 1 \right] (\text{Stator } I^2R)$$

$$= \left[\frac{(55) - (56)}{2} - 1 \right] (173)$$

(174) -- **TOTAL LOSSES** at 100% load - sum of all losses at 100% load

$$\begin{aligned} \text{Total Losses} = {} & (\text{Rotor } I^2R) + (F\ \&\ W) + (\text{Stator Teeth Loss}) \\ & + (\text{Stator Core Loss}) + (\text{Pole Face Loss}) \\ & + (\text{Damper Loss}) + (\text{Stator } I^2R) + (\text{Eddy Loss}) \end{aligned}$$

$$= (169) + (147) + (170) + (149) + (171) + (172) + (173) + (173a)$$

(175) -- **RATING IN WATTS** at 100% load

$$\text{Rating} = 3(E_{PH})(I_{PH})\sqrt{3}\ (\text{P.F.})\ \frac{(\%\ \text{Load})}{100}$$

$$= 3(4)(8)\sqrt{3}\ (9)(1.)$$

(176) -- **RATING & Σ LOSSES** = (175) + (174)

(177) -- **% LOSSES** $= \left[\Sigma\,\text{Losses} / \text{Rating} + \Sigma\,\text{Losses}\right] 100$

$$= \left[(174) / (177)\right] 100$$

(178) -- **% EFFICIENCY** = 100% - % Losses

$$= 100\% - (177)$$

Item (160) through (178) are 100% load calculations. These items can be recalculated for any load condition by simply inserting the values that correspond to the % load being calculated. The factor $\frac{(\%\ \text{Load})}{100}$ takes care of (I_{PH}) as it changes with load.

Note that values for F & W (147) and W_C (Stator Core Loss) (149) do not change with load, therefore they can be calculated only once.

NO-LOAD-SATURATION - The next series of calculations are for the no load saturation where the items are calculated for various voltage conditions. For the purposes of this manual, a sample set of calculations for item (179) through (190) are presented for 150% of rated voltage. The calculations for any other voltage can be obtained by simply using the values that correspond to the % load being calculated.

The no load saturation is not a standard output for the computer. When 0 is inserted in item (179) "No Load Sat" on input sheet, the computer will not calculate the no load saturation. When 1 is inserted in item (179) on input sheet, the computer will calculate the no load saturation at 80, 90, 100, 110, 120, 130, 140, 150, 160% of rated volts. There is a standard output sheet available, therefore the items will be read out to match the sequence of calculations that follow:

(179) -- VOLTS - Line volts

$$\text{Volts} = (\text{Per Unit Voltage})(\text{Rated Voltage})$$
$$= (1.5)(3)$$

(180) F_g' AIR GAP AMPERE TURNS

$$F_g' = (\text{Per Unit Voltage})(F_g)$$
$$= (1.5)(131)$$

(181) B_t' TOOTH DENSITY

$$B_t' = (\text{Per Unit Voltage})(B_t)$$
$$= (1.5)(127)$$

(182) E' TOOTH AMPERE TURNS PER POLE

Repeat (129) using density (181)

(183) B_C' CORE DENSITY

$$B_C' = (\text{Per Unit Voltage})(B_C)$$
$$= (1.5)(128)$$

(184) F_C' STATOR CORE AMPERE TURNS

Repeat (130) using density (183)

(185) F_S' **STATOR AMPERE TURNS**

$$F_S' = F_T' + F_C' = (182) + (184)$$

(186) ϕ_ℓ' **LEAKAGE FLUX**

$$\phi_\ell' = .00638 \left[(\lambda_s) + (\lambda_e) + (\lambda_{t\ell})\right]\left[(F_S') + (F_g')\right](\ell_P)$$

$$= .00638 \left[(88) + (86) + (87)\right]\left[(185) + (180)\right](76)$$

(187) ϕ_{PT}' **TOTAL FLUX / POLE**

$$\phi_{PT}' = \left[(\text{Per Unit Voltage})(\phi_P)\right] + \left[(\phi_\ell')\right]$$

$$= \left[(1.5)(126)\right]\left[(186)\right]$$

(188) B_P' **POLE DENSITY**

$$B_P' = (\phi_{PT}')/(a_P) = (187)/(85)$$

(189) F_P' **POLE AMPERE TURNS**

Repeat (141) using density (188)

(190) F_{NL}' **TOTAL AMPERE TURNS**

$$F_{NL}' = (F_g') + (F_S') + (F_P')$$

$$= (180) + (185) + (189)$$

COMPUTER PROCEDURE

(1) Insert the first output sheet to the typewriter and line up the carriage with the mark on the top of the sheet. Set single space.

(2) Clear core for the 1st pass only.

(3) Load the 1st pass object program.

(4) Load the 1st pass data.

(5) Punch outputs which are the input data for the 2nd pass.

(6) Reset and load 2nd pass.

(7) Repeat steps (3), (4), (5) and (6) for 2nd to 5th passes.

(8) For the 6th pass, data of the two magnetization curves, the first for stator and the second for the rotor, following the other data to be read in.

(9) If no load saturation data are required, outputs will be punched out from the 7th pass and be used in the 8th pass.

(10) Insert the second output sheet to the typewriter as in step (1) before processing the 8th pass.

(11) The two magnetization curves are included as input data in the 8th pass as in the 6th pass.

(1) The last item on the last card (input data of the 1st pass) is the Design Number.

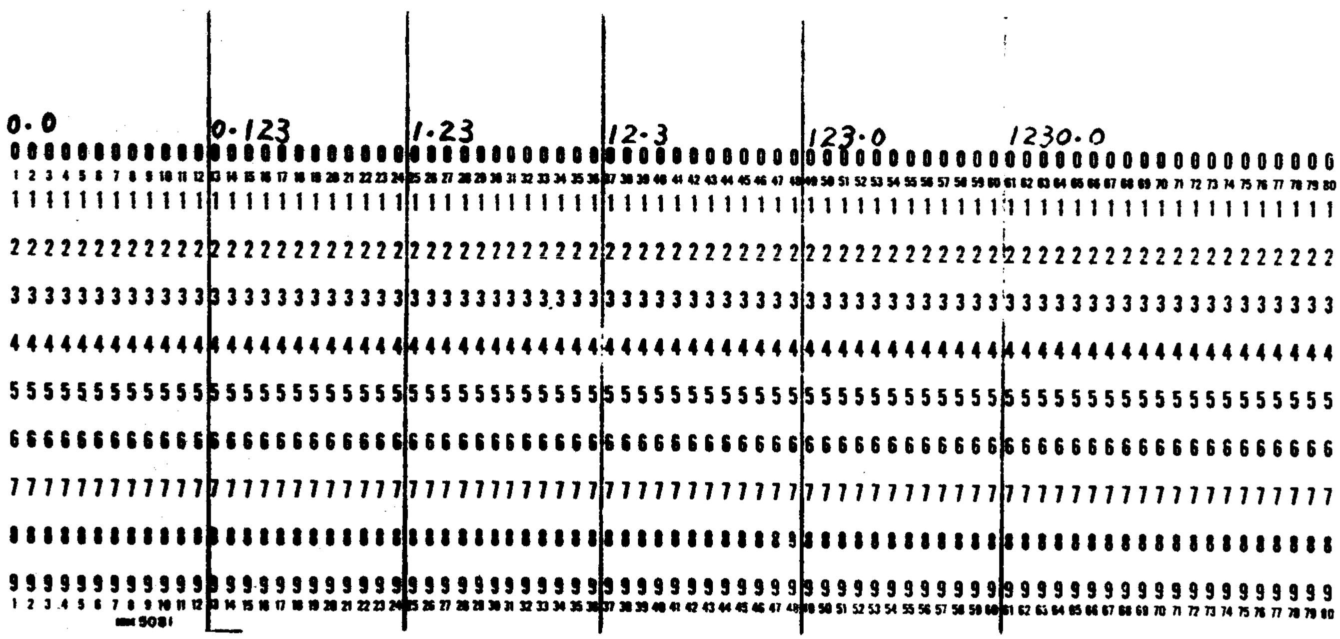
(2) A thick line is drawn every six items on the input sheet.

INPUT DATA: -

(1) All input data are provided on the input sheet. The data of the magnetization curves are provided separately.

(2) Data are punched on cards following the sequence of the input sheet, first the left hand column and then the right hand column.

(3) Each card consists of six data starting from column 1, 13, 25, 37, 49 and 61 consecutively.



(4) All data are in numerical and decimal form.

(5) The input sheet should be fully filled in.

(6) The magnetization curves are read in ampere turns per inch (magnetizing force) for every 5 Kilolines per square inch (induction) starting from 0 to 140, that is totally 29 points for each curve.

(7) Data for two magnetization curves are required. The first curve for the stator and the second for the rotor. If both are of the same kind of material, two identical sets are used.

(8) The first seven passes are to be used to complete the first output sheet and the 8th pass for the second output sheet.

(9) Number of cards as input data to each pass:

No. of Pass	Data	Magnetization Curve	Total
1st	15	0	15
2nd	16	0	16
3rd	17	0	17
4th	16	0	16
5th	17	0	17
6th	11	10	21
7th	9	0	9
8th	2	10	12

(10) Number of cards punched out from each pass:

No. of Pass	No. of Cards
1st	16
2nd	17
3rd	16
4th	17
5th	11

(10) Cont'd

No. of Pass	No. of Cards
6th	9
7th	2*
8th	0

* It is zero when no load saturation data are not required.

INPUT SYMBOL LISTING

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation	Remarks
(2)	Kva	VA	Generator KVA	
(3)	E	EE	Line volts	
(4)	E_{PH}	EP	Phase volts	
(5)	m	PN	Phases	
(5a)	f	F	Frequency	
(6)	p	PX	Poles	
(7)	Rpm	RPM	Speed	
(8)	I_{PH}	PI	Phase current	
(9)	P.F.	P.F.	Power factor	
(9a)	K_c	CK	Adjustment factor	
(10)	L.P.	POL	Load points	
(11)	d	DI	Stator inside diameter	
(12)	D	DU	Stator outside diameter	
(13)	ℓ	CL	Gross core length	
(14)	n_v	HV	Number of radial ducts	
(15)	b_v	BV	Width of radial ducts	
(16)	K_i	SF	Stacking factor	
(18)	--	SML	Stator material	
(19)	k	WL	Watts/lb.	
(20)	B	BK	Density	

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation	Remarks
(21)	--	ZZ	Type of slot	1.0 : a 2.0 : b 3.0 : c 4.0 : d 5.0 : e
(22)	b_o	BO		
(22)	b_1	B1		
(22)	b_2	B2		
(22)	b_3	B3		
(22)	b_s	BS		
(22)	h_o	HO		
(22)	h_1	HX	Stator slot dimensions	
(22)	h_2	HY		
(22)	h_3	HZ		
(22)	h_s	HS		
(22)	h_t	HT		
(22)	h_w	HW		
(23)	Q	QQ		
(28)	--	W	Type of winding	0.0 delta 1.0 wye
(29)	--	RF	Type of coil	0.0 random 1.0 formed
(30)	n_s	SC	Conductors/slot	
(31)	y	YY	Throw	
(32)	c	C	Parallel paths	

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation	Remarks
(33)	--	DW	Strand dia. or width	
(34)	N_{st}	SN	Strands/conductor	
(35)	d_b	DB	Diameter of pin	
(36)	ℓ_{e2}	CE	Coil extension straight portion	
(37)	h_{st}	SH	Uninsulated height of strand	
(38)	h'_{st}	SD	Distance between CL of strand	
(39)	--	DT	Stator strand thickness	
(40)	T_{sk}	SK	Stator slot skew	
(50)	$X_s^{o}C$	T1	Expected operating temperature ^{o}C	
(51)	$\rho_s(20^{o}C)$	RS	Resistivity of stator winding	
(59)	g_{min}	GC	Minimum air gap	
(59a)	g_{max}	GP	Maximum air gap	
(71)	C_1	C1	Ratio max. to min. of fundamental	
(72)	C_w	CW	Winding constant	
(73)	C_p	CP	Ratio of ave. to max. field form	
(48)	L_E	EL	End extension one turn	
(74)	C_m	CM	Demagnetizing factor	
(75)	C_q	CQ	Cross magnetizing factor	
(76)	b_h	BH	Pole head width	

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation	Remarks
(76)	b_p	BP	Pole body width	
(76)	h_h	HH	Pole head height	
(76)	h_f	HF	Pole body height	
(76)	ℓ_p	SQ	Pole body length	
(76)	ℓ_n	PL	Pole head length	
(77)	α	PE	Pole embrace	
(11a)	d_r	DR	Rotor diameter	
(16)	K_i	RK	Stacking factor rotor	
(18)	--	RML	Rotor material	
(108b)	--	WR	Weight of rotor iron	
(151)	K_1	D1	Pole face loss factor	
(89)	b_{bo}	WO	Width of slot opening (Damper slot)	
(89)	h_{bo}	HD	Height of slot opening (Damper slot)	
(90)	--	DD	Damper bar dia. or width	
(89)	h_{b1}	H	Rectangular bar thickness	
(89)	b_{b1}	B	Rectangular slot width	
(92)	n_b	BN	Number of damper bars	
(93)	ℓ_b	SB	Damper bar length	
(94)	τ_b	TB	Damper bar pitch	
(95)	ρ_D	RE	Resistivity of damper bar at 20 °C	

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation	Remarks
(96)	X_D^oC	T3	Expected operating bar temp. in ^oC	
(99)	N_p	PT	Number of field turns	
(100)	ℓ_{tr}	FE	Mean length of field turns	
(101)	--	RD	Field conductor diameter or width	
(102)	--	RT	Field conductor thickness	
(103)	X_f^oC	T2	Expected operating temp. in ^oC	
(104)	$\rho_f(20^oC)$	RR	Field conductor resistivity at 20^oC	
(179)	--	SNL	No load saturation	0.0 no 1.0 yes
(147)	F&W	WF	Friction & windage loss	
		DNO	Design number	
(174)	--	SP	Total loss (F.L.)	
(175)	--	VA	Rating in KW (F.L.)	
(176)	--	P	Rating + losses (F.L.)	
(177)	--	PM	Percent losses (F.L.)	
(178)	--	E	Percent efficiency (F.L.)	

OUTPUT SYMBOL LISTING

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(17)	ℓ_s	SS	Solid core length
(24)	h_c	HC	Depth below slot X 2
(26)	τ_s	TS	Slot pitch
(27)	$\tau_{s\ 1/3}$	TT	Slot pitch 1/3 dist. up
(42)	K_{sk}	FS	Skew factor
(43)	K_d	DF	Distribution factor
(44)	K_p	CF	Pitch factor
(45)	N_e	EC	Effective conductors
(46)	a_c	AC	Strand area
(47)	S_s	S	Current density (stator)
(49)	ℓ_t	HM	1/2 mean turn
(53)	$R_{PH(cold)}$	RG	Cold stator resistance at 20 ^oC
(54)	$R_{PH(hot)}$	RP	Hot stator resistance at X ^oC
(55)	$EF_{(top)}$	ET	Eddy factor top
(56)	$EF_{(bot)}$	EB	Eddy factor bottom
(62)	λ_i	PC	Stator conductor permeance
(63)	λ_E	EW	End permeance
(65)	--	WC	Weight of stator copper
(66)	--	WI	Weight of stator iron
(41)	τ_P	TP	Pole pitch
(85)	a_p	AP	Pole area

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(86)	λ_{el}	ES	Pole end leakage permeance
(87)	λ_{tl}	TL	Pole tip leakage permeance
(88)	λ_{sl}	SL	Pole side leakage permeance
(89)	a_{cf}	AS	Field cond. area
(90)	$R_{f(cold)}$	FK	Cold field resistance at $20^{\circ}C$
(91)	$R_{f(hot)}$	FR	Hot field resistance at $X^{\circ}C$
(108a)	--	RC	Weight of field copper
(108b)	--	WR	Weight of field iron
(98a)	V_r	VR	Peripheral speed
(132)	T'_{do}	TC	Open circuit time constant
(133)	T_a	TA	Armature time constant
(134)	T'_d	T5	Transient time constant
(135)	T''_d	T4	Subtransient time constant
(136)	F_{sc}	FSC	Short circuit ampere turns
(137)	SCR	SCR	Short circuit ratio
(67)	K_s	CC	Carter coefficient
(68)	--	GA	Air gap area
(70)	λ_a	AG	Air gap permeance
(69)	g_e	GE	Effective air gap
(71)	C_1	C1	Ratio max to fundamental
(72)	C_w	CW	Winding constant
(73)	C_p	CP	AVE/maximum field form
(48)	L_E	EL	End extension one turn

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(74)	C_M	CM	Demagnetization factor
(75)	C_q	CQ	Cross magnetizing factor
(78)	A	A	Ampere conductors/in.
(79)	X	XR	Reactance factor
(80)	X_ℓ	XL	Leakage reactance
(81)	X_{ad}	XL	Reactance direct axis
(82)	X_{aq}	XQ	Reactance quadrature axis
(83)	X_d	XA	Synchronous reactance direct axis
(84)	X_q	XB	Synchronous reactance quadrature axis
(112)	X_F	XF	Field leakage reactance
(113)	L_F	SI	Field self inductance
(115)	X_{Dd}	X1	Leakage reactance in direct axis
(117)	X_{Dq}	X2	Leakage reactance in quadrature axis
(118)	X'_{du}	XU	Unsaturated transient reactance
(119)	X'_d	XS	Saturated transient reactance
(120)	X''_d	XX	Subtransient reactance direct axis
(121)	X''_q	XY	Subtransient reactance quadrature axis
(122)	X_2	XN	Negative sequence reactance
(123)	X_o	XO	Zero sequence reactance
(124)	ϕ_T	TG	Total flux
(126)	ϕ_p	FQ	Flux per pole

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(125)	B_g	BG	Gap density
(127)	B_t	TE	Tooth density
(128)	B_c	BX	Core density
(129)	F_t	FX	Tooth ampere turns
(130)	F_c	AT	Core ampere turns
(130)	F_g	FH	Gap ampere turns
(138)	ϕ_ℓ	UX	Leakage flux (No load)
(139)	ϕ_{PT}	TF	Pole flux (N. L.)
(140)	B_p	PD	Pole density (N. L.)
(141)	F_p	FA	Pole ampere turns (N. L.)
(142)	F_{NL}	FN	Total ampere turns (N. L.)
(143)	I_{FNL}	FI	Field amperes (N. L.)
(144)	S_F	CD	Current density (Field) (N. L.)
(145)	E_F	EF	Field volts (N. L.)
(146)	I^2R_R	PR	Rotor loss (N. L.)
(147)	F&W	WF	Friction & windage loss (N. L.)
(148)	W_{TNL}	ST	Stator tooth loss (N. L.)
(149)	W_c	WQ	Stator core loss (N. L.)
(150)	W_{PNL}	WN	Pole face loss (N. L.)
(157)	W_{PNL}	DL	Damper loss (N. L.)
(158)	I^2R_s	PS	Stator copper loss (N. L.)
(158a)	--	EX	Eddy loss (N. L.)
(159)	--	SP	Total loss (N. L.)

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(160)	$\phi_{\ell\ell}$	GZ	Leakage flux (Full load)
(162)	ϕ_{PTL}	GL	Pole flux (F. L.)
(163)	B_{PL}	FD	Pole density (F. L.)
(164)	F_{PL}	FX	Pole ampere turns (F. L.)
(165)	F_{FL}	FB	Total ampere turns (F. L.)
(166)	I_{FFL}	FI	Field amperes (F. L.)
(167)	S_F	CD	Current density (F. L.)
(168)	E_{FFL}	EF	Field volts (F. L.)
(169)	I^2R_R	PR	Rotor loss (F. L.)
(147)	F&W	WF	Friction & windage (F. L.)
(170)	W_{TFL}	ST	Stator tooth loss (F. L.)
(149)	W_C	WQ	Stator core loss (F. L.)
(171)	W_{PFL}	PP	Pole face loss (F. L.)
(172)	W_{DFL}	DL	Damper loss (F. L.)
(173)	I^2R_s	PS	Stator copper loss (F. L.)
(173a)	--	EX	Eddy loss (F. L.)

```
      DIMENSION DA(8),DX(6),DY(8),DZ(8)
    1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
    2 FORMAT(40X F12.5)
    3 FORMAT(9X F12.5,2X F12.5)
   33 READ1, VA,EE,EP,PN,F,PX
      READ1, RPM,PI,PF,CK,POL,DI
      READ1, DU,CL,HV,BV,SF,SML
      READ1, WL,BK,ZZ,BO,B1,B2
      READ1, B3,BS,HO,HX,HY,HZ
      READ1, HS,HT,HW,QQ,W,RF
      READ1, SC,YY,C,DW,SN,DB
      READ1, CE,SH,SD,DT,SK,T1
      READ1, RS,GC,GP,C1,CW,CP
      READ1, EL,CM,CQ,BH,BP,HH
      READ1, HF,SQ,PL,PE,DR,RK
      READ1, RML,WR,D1,WO,HD,DD
      READ1, H,B,BN,SB,TB,RE
      READ1, T3,PT,FE,RD,RT,T2
      READ1, RR,SNL,WF,DNO
      PRINT2,DNO
      SS=SF*(CL-HV*BV)
      HC=(DU-DI-2.0*HS)*0.5
      ZY=0.7*HS
      IF(HC-ZY) 33,33,5
    5 QN=QQ/(PX*PN)
      TS=3.142*DI/QQ
      IF(ZZ-4.0)29,30,29
   29 TT=(0.667*HS+DI)*3.142/QQ
      GO TO 31
```

```
30 TT=((2.0*HO+BS)*0.66+DI)*3.1416/QQ
31 IF(ZZ-1.0)6,6,7
 6 CC=(5.0*GC+BS)*TS/((5.0*GC+BS)*TS-BS*BS)
   GO TO 8
 7 QC=(4.44*GC+0.75*BO)*TS
   CC=QC/(QC-BO*BO)
 8 CS=YY/(PN*QN)
   TP=3.142*DI/PX
   FS=SIN(1.571*SK/TP)*TP/(1.571*SK)
   ZY=PX*PN
   U=0.0
 9 U=U+1.0
   DM=U*ZY
   IF(QQ-DM)11,10,9
10 DF=SIN(1.571/PN)/(QN*SIN(1.571/(PN*QN)))
   GO TO 12
11 DF=SIN(1.571/PN)/(QQ*SIN(1.571/(QQ*PN)))
12 CF=SIN(YY*1.571/(PN*QN))
   EC=QQ*SC*CF*FS/C
   IF(DT) 13,13,14
13 AC=0.785*DW*DW
   GO TO 24
14 ZY=0.0
   DA(1)=0.05
   DA(2)=0.072
   DA(3)=0.125
   DA(4)=0.165
   DA(5)=0.225
```

```
      DA(6)=0.438
      DA(7)=0.688
      DA(8)=1.5
      DX(1)=0.000124
      DX(2)=0.00021
      DX(3)=0.00021
      DX(4)=0.00084
      DX(5)=0.00189
      DX(6)=0.00189
      DY(1)=0.000124
      DY(2)=0.000124
      DY(3)=0.00084
      DY(4)=0.00084
      DY(5)=0.00189
      DY(6)=0.00335
      DY(7)=0.00754
      DY(8)=0.03020
      DZ(1)=0.000124
      DZ(2)=0.000124
      DZ(3)=0.000124
      DZ(4)=0.00335
      DZ(5)=0.00335
      DZ(6)=0.00754
      DZ(7)=0.0134
      DZ(8)=0.0302
   15 JA=0
      JB=0
      JC=0
      JD=0
```

```
16 JA=JA+1
   JB=JB+1
   JC=JC+1
   JD=JD+1
   IF(DT-DA(JA))17,17,16
17 IF(DW-0.188)18,18,19
18 CY=DX(JB-1)
   CZ=DX(JB)
   GO TO 22
19 IF(DW-0.75)20,20,21
20 CY=DY(JC-1)
   CZ=DY(JC)
   GO TO 22
21 CY=DZ(JD-1)
   CZ=DZ(JD)
22 D=CY+(CZ-CY)*(DT-DA(JA-1))/(DA(JA)-DA(JA-1))
   IF(ZY)23,23,27
23 AC=DT*DW-D
24 IF(RT)25,25,26
25 AS=0.785*RD*RD
   GO TO 28
26 ZY=1.0
   GO TO 15
27 AS=RT*RD-D
28 S=PI/(C*AC)
   PUNCH1,VA,EE,EP,PN,F,PX
   PUNCH1,RPM,PI,PF,CK,POL,DI
```

```
PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,BO,B1,B2
PUNCH1,B3,BS,HO,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,T1
PUNCH1,RS,GC,GP,C1,CW,CP
PUNCH1,EL,CM,CQ,BH,BP,HH
PUNCH1,HF,SQ,PL,PE,DR,RK
PUNCH1,CC,WR,D1,WO,HD,DD
PUNCH1,H,B,BN,SB,TB,RE
PUNCH1,T3,PT,FE,RD,RT,T2
PUNCH1,RR,SNL,WF,CS,AS,FS
PUNCH1,TP,DF,CF,EC,AC,S
PAUSE
END
```

```
 1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
 3 FORMAT(9X F12.5,2X F12.5)
   READ1, VA,EE,EP,PN,F,PX
   READ1, RPM,PI,PF,CK,POL,DI
   READ1, DU,CL,SS,HC,SF,QN
   READ1, WL,BK,ZZ,BO,B1,B2
   READ1, B3,BS,HO,HX,HY,HZ
   READ1, HS,HT,HW,QQ,W,RF
   READ1, SC,YY,C,TS,SN,DB
   READ1, CE,SH,SD,TT,SK,T1
   READ1, RS,GC,GP,C1,CW,CP
   READ1, EL,CM,CQ,BH,BP,HH
   READ1, HF,SQ,PL,PE,DR,RK
   READ1, CC,WR,D1,WO,HD,DD
   READ1, H,B,BN,SB,TB,RE
   READ1, T3,PT,FE,RD,RT,T2
   READ1, RR,SNL,WF,CS,AS,FS
   READ1, TP,DF,CF,EC,AC,S
   GA=3.142*DI*CL
   AG=6.38*DI/(PX*GC*CC)
   GE=CC*GC
   IF(C1) 44,43,44
43 C1=(0.649*LOG(PE)+1.359)*((GC/GP)**0.352)
44 IF(CW)45,45,46
45 CW=0.707*EE*C1*DF/(EP*PN)
46 TG=6000000.0*EE/(CW*EC*RPM)
```

```
   BG=TG/GA
   IF(CP)47,47,48
47 CP=(GC/GP)**0.41*PE*(LOG(GC/TP)*.0378+1.191)
48 FQ=TG*CP/PX
   IF(ZZ-3.0)49,50,51
49 SM=TT-BS
   GO TO 53
50 SM=TT-B2
   GO TO 53
51 IF(ZZ-4.0)50,52,49
52 SM=TT-BS*(0.554-0.888*HO/BS)
53 TE=TG/(QQ*SS*SM)
   BX=0.5*FQ/(HC*SS)
   IF(EL) 54,54,62
54 IF(RF) 55,55,61
55 IF(PX-2.0) 56,56,57
56 U=1.3
   GO TO 60
57 IF(PX-4.0) 58,58,59
58 U=1.5
   GO TO 60
59 U=1.7
60 EL=3.142*U*YY*(DI+HS)/QQ+0.5
   GO TO 62
61 EL=2.0*CE+(3.142*(0.5*HX+DB))+(YY*TS*TS/(SQRT(TS*TS-BS*BS)))
62 HM=CL+EL
   RY=SC*QQ*HM/(PN*AC*C*C)
   RX=RS*0.000001
```

```
      RB=(T1+234.5)*0.00394*RX
      RG=RX*RY
      RP=RB*RY
      AA=0.584+(SN*SN-1.0)*0.0625*(SD*CL/(SH*HM))**2.0
      AB=(SH*SC*F*AC/(BS*RB*1000000.0))**2.0
      ET=AA*AB*0.00335+1.0
      EB=ET-0.00168*AB
      IF(CM)63,63,64
   63 AA=SIN(3.142*PE)
      AB=SIN(1.571*PE)*4.0
      CM=(3.142*PE+AA)/AB
   64 A=PI*SC*CF/(C*TS)
      PRINT3,SS,CC,HC,GA,TS,AG,TT,GE,FS,C1,DF,CW,CF,CP,EC,EL,AC,CM
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,DI
      PUNCH1,DU,CL,SS,HC,SF,QN
      PUNCH1,WL,BK,ZZ,B0,B1,B2
      PUNCH1,B3,BS,H0,HX,HY,HZ
      PUNCH1,HS,HT,HW,QQ,W,GE
      PUNCH1,SC,YY,C,TS,BG,TG
      PUNCH1,FQ,TE,BX,TT,HM,SM
      PUNCH1,RG,GC,RP,C1,CW,CP
      PUNCH1,EL,CM,CQ,BH,BP,HH
      PUNCH1,HF,SQ,PL,PE,DR,RK
      PUNCH1,CC,WR,D1,W0,HD,DD
      PUNCH1,H,B,BN,SB,TB,RE
      PUNCH1,T3,PT,FE,RD,RT,T2
      PUNCH1,RR,SNL,WF,CS,AS,ET
```

```
PUNCH1,TP,DF,CF,EB,AC,S
PUNCH1,AG,A
PAUSE
END
```

```
  1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
  3 FORMAT(9X F12.5,2X F12.5)
    READ1, VA,EE,EP,PN,F,PX
    READ1, RPM,PI,PF,CK,POL,DI
    READ1, DU,CL,SS,HC,SF,QN
    READ1, WL,BK,ZZ,BO,B1,B2
    READ1, B3,BS,HO,HX,HY,HZ
    READ1, HS,HT,HW,QQ,W,GE
    READ1, SC,YY,C,TS,BG,TG
    READ1, FQ,TE,BX,TT,HM,SM
    READ1, RG,GC,RP,C1,CW,CP
    READ1, EL,CM,CQ,BH,BP,HH
    READ1, HF,SQ,PL,PE,DR,RK
    READ1, CC,WR,D1,WO,HD,DD
    READ1, H,B,BN,SB,TB,RE
    READ1, T3,PT,FE,RD,RT,T2
    READ1, RR,SNL,WF,CS,AS,ET
    READ1, TP,DF,CF,EB,AC,S
    READ1, AG,A
    IF(CQ)69,69,70
 69 AA=1.571*PE
    AB=3.1416*PE
    CQ=(0.5*COS(AA)+AB-SIN(AB))/(4.0*SIN(AA))
 70 XR=.0707*A*DF/(C1*BG)
    IF(PN-2.0)71,71,72
 71 FF=YY/(PN*QN)
    GO TO 75
 72 IF(ZZ-5.0) 74,73,74
```

```
73 FF=1.0
   GO TO 75
74 FF=0.25*(3.0*YY/(PN*QN)+1.0)
75 CX=FF/(CF*CF*DF*DF)
   Z=CX*20.0/(PN*QN)
   BT=3.142*DI/QQ-BO
   ZA=BT*BT/(16.0*TS*GC)
   ZB=0.35*BT/TS
   ZC=HO/BO
   ZD=HX*0.333/BS
   ZE=HY/BS
   IF(ZZ-2.0) 76,77,78
76 PC=Z*(ZE+ZD+ZA+ZB)
   GO TO 82
77 PC=Z*(ZC+(2.0*HT/(BO+BS))+(HW/BS)+ZD+ZA+ZB)
   GO TO 82
78 IF(ZZ-4.0) 79,80,81
79 PC=Z*(ZC+(2.0*HT/(BO+B1))+(2.0*HW/(B1+B2))+(HX*0.333/B2)+ZA+ZB)
   GO TO 82
80 PC=Z*(ZC+0.62)
   GO TO 82
81 PC=Z*(ZE+ZD+(0.5*GC/TS)+(0.25*TS/GC)+0.6)
82 EK=EL/(10.0**(0.103*YY*TS+0.402))
   IF(DI-8.0) 83,83,84
83 EK=SQRT(EK)
84 ZF=.612*LOG(10.0*CS)
   EW=6.28*EK*ZF*(TP**(0.62-(0.228*LOG(ZF))))/(CL*DF*DF)
   IF(PN-3.0)85,86,86
85 ZC=0.1*DI*SIN(3.0*YY/(PN*QN))*1.57/(PX*GE*CF)
```

```
      GO TO 87
86    ZC=0.0
87    XL=(PC+EW+ZC)*XR
      XD=XR*AG*C1*CM
      XQ=XR*CQ*AG
      WC=0.321*SC*QQ*AC*HM
      ZA=3.1416*(DI+HS)/QQ
      IF(ZZ-3.0) 88,89,88
88    TM=ZA-BS
      GO TO 90
89    TM=ZA-(B1+(1.0-0.5/(1.0-(HO+HT)/HS))*(B3-B1))
90    PRINT3,S,CQ,HM,A,RG,XR,RP,XL,ET,XD,EB,XQ
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,DI
      PUNCH1,DU,CL,SS,HC,PC,QN
      PUNCH1,WL,BK,ZZ,BO,XD,XQ
      PUNCH1,XR,BS,XL,HX,HY,HZ
      PUNCH1,HS,WC,AC,QQ,W,GE
      PUNCH1,SC,YY,C,TS,BG,TG
      PUNCH1,FQ,TE,BX,TT,EW,AG
      PUNCH1,RG,GC,RP,C1,TP,CP
      PUNCH1,DF,CM,CF,BH,BP,HH
      PUNCH1,HF,SQ,PL,EB,DR,RK
      PUNCH1,CC,WR,D1,WO,HD,DD
      PUNCH1,H,B,BN,SB,TB,RE
      PUNCH1,T3,PT,FE,RD,RT,T2
      PUNCH1,RR,SNL,WF,CS,AS,ET
      PUNCH1,TM
      PAUSE
      END
```

```
  1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
  3 FORMAT(9X F12.5,2X F12.5)
    READ1, VA,EE,EP,PN,F,PX
    READ1, RPM,PI,PF,CK,POL,DI
    READ1, DU,CL,SS,HC,PC,QN
    READ1, WL,BK,ZZ,BO,XD,XQ
    READ1, XR,BS,XL,HX,HY,HZ
    READ1, HS,WC,AC,QQ,W,GE
    READ1, SC,YY,C,TS,BG,TG
    READ1, FQ,TE,BX,TT,EW,AG
    READ1, RG,GC,RP,C1,TP,CP
    READ1, DF,CM,CF,BH,BP,HH
    READ1, HF,SQ,PL,EB,DR,RK
    READ1, CC,WR,D1,WO,HD,DD
    READ1, H,B,BN,SB,TB,RE
    READ1, T3,PT,FE,RD,RT,T2
    READ1, RR,SNL,WF,CS,AS,ET
    READ1, TM
    WI=(TM*QQ*SS*HS+(DU-HC)*3.142*HC*SS)*0.283
    AN=0.0
100 AN=AN+0.005
    AL=COS(AN)
    IF(PF-AL) 100,100,101
101 VR=0.262*DR*RPM
    AP=BP*SQ*RK
    SL=HF/((DR-2.0*HH-0.5*HF)*3.142/PX-BP)
    ES=((PL-CL)*2.0+HF+0.25*BP)/CL
```

```
      TL=(HH+GC-TP/18.0)*2.0/(TP-BH)
      FH=BG*GE/0.00319
      ZG=PT*PX*FE*0.000001/AS
      FK=RR*ZG
      FR=(T2+234.5)*FK*0.00394
      RC=0.321*PT*PX*FE*AS
      RL=(1.5*TL+SL)*4.25+6.38*ES
      XF=(1.0-C1/((1.273*RL/AG+2.0*CP)*CM))*XD
      S1=(1.571*CP*AG+RL)*PT*PT*PX*SQ*0.00000001
      IF(DD)103,103,102
  102 ZG=0.62
      GO TO 104
  103 ZG=0.333*H/B
  104 BD=(HD/WO+ZG+0.5)*6.38
      BE=(BH-(BN-1.0)*TB)*2.127/GE
      P1=(BD+BE)*RL*COS((BN-1.0)*TB*1.572/TP)/(BD+BE+RL)
      X1=XR*P1
      P2=(HD/WO+ZG+0.5+GC/TB)*20.0*TB/TP
      X2=XR*P2
      XA=XL+XD
      XB=XL+XQ
      XU=XL+XF
      XS=0.88*XU
      IF(BN)105,105,106
  105 XX=XS
      XY=XB
      GO TO 107
  106 XX=XL+X1
```

```
    XY=XL+X2
107 XN=(XX+XY)*0.5
    TC=SI/FR
    RA=PN*PI*PI*RP*0.001/VA
    TA=XN/(628.4*F*RA)
    T5=XS*TC/XA
    IF(F-60.0)108,108,109
108 T4=0.035
    GO TO 110
109 T4=0.005
110 IF(WF)111,111,112
111 WF=DR**2.5*(RPM**1.5)*PL*0.00000252
112 WQ=(DU-HC)*1.42*HC*SS*(BX/BK)**2.0*WL
    WT=(TT-BS)*QQ*SS*HS*0.453*(TE/BK)**2.0*WL
    PRINT3,PC,XA,EW,XB,WC,XF,WI,SI,TP,X1,AP,X2,ES,XU,TL,XS,SL,XX,AS,X
    PRINT3,FK,XN
    PUNCH1,VA,EE,EP,PN,F,PX
    PUNCH1,RPM,PI,PF,CK,POL,DI
    PUNCH1,DU,CL,SS,HC,PC,QN
    PUNCH1,WL,BK,ZZ,BO,XD,XQ
    PUNCH1,XR,BS,TL,HX,HY,HZ
    PUNCH1,HS,ES,AC,QQ,W,GE
    PUNCH1,SC,YY,C,TS,BG,TG
    PUNCH1,FQ,TE,BX,TT,EW,AG
    PUNCH1,RG,GC,RP,C1,AP,P2
    PUNCH1,DF,SL,CF,FH,BP,HH
    PUNCH1,HF,SQ,PL,EB,DR,RK
    PUNCH1,CC,WR,D1,WO,TC,DD
```

```
PUNCH1,H,B,BN,SB,TB,RE
PUNCH1,T3,PT,VR,RD,RT,WT
PUNCH1,WQ,SNL,WF,CS,AS,ET
PUNCH1,FK,FR,XA,XB,T5,T4
PUNCH1,AN,AL,RC,TA,HD
PAUSE
END
```

```
    1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
    3 FORMAT(9X F12.5,2X F12.5)
      READ1, VA,EE,EP,PN,F,PX
      READ1, RPM,PI,PF,CK,POL,DI
      READ1, DU,CL,SS,HC,PC,QN
      READ1, WL,BK,ZZ,BO,XD,XQ
      READ1, XR,BS,TL,HX,HY,HZ
      READ1, HS,ES,AC,QQ,W,GE
      READ1, SC,YY,C,TS,BG,TG
      READ1, FQ,TE,BX,TT,EW,AG
      READ1, RG,GC,RP,C1,AP,P2
      READ1, DF,SL,CF,FH,BP,HH
      READ1, HF,SQ,PL,EB,DR,RK
      READ1, CC,WR,D1,WO,TC,DD
      READ1, H,B,BN,SB,TB,RE
      READ1, T3,PT,VR,RD,RT,WT
      READ1, WQ,SNL,WF,CS,AS,ET
      READ1, FK,FR,XA,XB,T5,T4
      READ1, AN,AL,RC,TA,HD
      GT=BS/GC
      IF(GT-3.75) 113,114,114
  113 AA=10.0**0.178/((GT-1.0)**0.334)
      GO TO 115
  114 AA=10.0**0.11/((GT-1.0)**0.174)
  115 GF=AA*PI*SC/(C*FH)
      IF(SC-1.0)120,121,122
  120 A5=0.0
```

```
      GO TO 129
  121 AX=1.0
      AY=1.0
      GO TO 125
  122 AX=3.0*YY/(PN*QN)-2.0
      IF(CS-0.667)123,124,124
  123 AY=1.5*YY/(PN*QN)-0.25
      GO TO 125
  124 AY=.75*YY/(PN*QN)+0.25
  125 A3=AX*P2/AY
      A4=0.07*AX*AG/(CF*CF)
      IF(AX)120,120,126
  126 IF(BN)127,127,128
  127 A5=A4
      GO TO 129
  128 A5=(A4+A3)/(A3*A4)
  129 IF(W)130,130,131
  130 XO=0.0
      GO TO 132
  131 AA=(3.0*HZ+HX)*1.667/(PN*QN*CF*CF*DF*DF*BS)
      XO=((PC+A5)*AX/AY+AA+0.2*EW)*XR
  132 D2=BG**2.5*0.000061
      D3=(0.0167*QQ*RPM)**1.65*0.000015147
      IF(TS-0.9) 133,133,134
  133 D4=TS**1.285*0.81
      GO TO 137
  134 IF(TS-2.0) 135,135,136
  135 D4=TS**1.145*0.79
```

```
      GO TO 137
136   D4=TS**0.79*0.92
137   D7=BO/GC
      IF(D7-1.7) 138,138,139
138   D5=D7**2.31*0.3
      GO TO 144
139   IF(D7-3.0) 140,140,141
140   D5=D7**2.0*0.35
      GO TO 144
141   IF(D7-5.0) 142,142,143
142   D5=D7**1.4*0.625
      GO TO 144
143   D5=D7**0.965*1.38
144   D6=10.0**(0.932*C1-1.606)
      BA=3.142*D1*CL
      WN=D1*D2*D3*D4*D5*D6*BA
      UY=(SL+ES+TL)*SQ*0.00638
      AA=WO/(GC*CC)
      IF(AA-0.65)145,145,146
145   VT=LOG(10.0*AA)*(-0.242)+0.59
      GO TO 147
146   VT=0.327-(AA*0.266)
147   UZ=(DU-HC)*0.7850/PX
      EZ=(ET+EB)*0.5-1.0
      AA=PN*PI*PI
      PU=AA*RG
      PV=AA*RP
      VV=EE*PI*PF*1.732
```

```
FSC=XA*FH*0.01
PRINT3,FR,XO,RC,TG,WR,FQ,VR,BG,TC,TE,TA,BX
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,CK,POL,TB
PUNCH1,BO,GC,HH,HF,SQ,DR
PUNCH1,SB,RE,T3,PT,T5,T4
PUNCH1,WO,DD,H,BN,GF,VT
PUNCH1,SNL,TS,CC,BG,FK,AP
PUNCH1,FQ,TE,BX,FR,XD,FH
PUNCH1,WQ,WT,AN,AL,XA,WF
PUNCH1,AS,HS,B,GE,BP,XB
PUNCH1,WN,UY,UZ,EZ,PU,VV
PUNCH1,FSC,PV,HD
PAUSE
END
```

```
      DIMENSION FY(5),PA(5),ED(5),GX(5),GZ(5),GL(5),FD(5),FX(5),FB(5)
      DIMENSION FI(5),EF(5),CD(5),Q(4),R(58)
    1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
    3 FORMAT(9X F12.5,2X F12.5)
    4 FORMAT (F11.3,8X F11.3,F11.3,F11.3,F11.3)
      READ1, VA,EE,EP,PN,F,PX
      READ1, RPM,PI,PF,CK,POL,TB
      READ1, BO,GC,HH,HF,SQ,DR
      READ1, SB,RE,T3,PT,T5,T4
      READ1, WO,DD,H,BN,GF,VT
      READ1, SNL,TS,CC,BG,FK,AP
      READ1, FQ,TE,BX,FR,XD,FH
      READ1, WQ,WT,AN,AL,XA,WF
      READ1, AS,HS,B,GE,BP,XB
      READ1, WN,UY,UZ,EZ,PU,VV
      READ1, FSC,PV,HD
      READ1, R(1),R(2),R(3),R(4),R(5),R(6)
      READ1, R(7),R(8),R(9),R(10),R(11),R(12)
      READ1, R(13),R(14),R(15),R(16),R(17),R(18)
      READ1, R(19),R(20),R(21),R(22),R(23),R(24)
      READ1, R(25),R(26),R(27),R(28),R(29)
      READ1, R(30),R(31),R(32),R(33),R(34),R(35)
      READ1, R(36),R(37),R(38),R(39),R(40),R(41)
      READ1, R(42),R(43),R(44),R(45),R(46),R(47)
      READ1, R(48),R(49),R(50),R(51),R(52),R(53)
      READ1, R(54),R(55),R(56),R(57),R(58)
      GO TO 199
```

```
200 VQ=0.0
202 RM=R(L)
    L=L+1
    RN=R(L)
    VL=VQ+5.0
    IF(VL-BF) 203,203,204
203 VQ=VL
    GO TO 202
204 Q(J)=(RN-RM)*(BF-VQ)/5.0+RM
    GO TO (208,209,210,214),J
199 L=1
    J=1
    BF=BX
    GO TO 200
208 AT=UZ*Q(J)
    L=1
    J=2
    BF=TE
    GO TO 200
209 FT=Q(J)*HS
    SA=FT+AT
    UX=(SA+FH)*UY
    TF=FQ+UX
    PD=TF/AP
    J=3
    L=30
    BF=PD
    GO TO 200
210 FA=(HF+HH)*Q(J)
```

```
      FN=SA+FA+FH
      SCR=FN/FSC
      PRINT3,T5,FT,T4,AT,FSC,FH
  221 FORMAT(9X F12.5/)
      PRINT221,SCR
      YL=0.000001
      FW=FK
      M=1
  211 Y=100.0/YL
      FY(M)=ATAN((BX/Y+SIN(AN))/AL)
      PA(M)=FY(M)-AN
      ED(M)=XA*SIN(FY(M))/Y+COS(PA(M))
      GX(M)=(ED(M)-(0.93*XD*SIN(FY(M))/Y))*FQ
      IF(PF-0.95)213,213,212
  212 GX(M)=GX(M)*CK
  213 GZ(M)=((1.0+COS(AN))*FT+AT+(FH*ED(M)))*UX/(FH+SA)
      GL(M)=GX(M)+GZ(M)
      FD(M)=GL(M)/AP
      J=4
      L=30
      BF=FD(M)
      GO TO 200
  214 FX(M)=(HF+HH)*Q(J)
      FB(M)=(1.0+COS(PF))*FT+AT+FX(M)+ED(M)*FH
      FI(M)=FB(M)/PT
      EF(M)=FI(M)*FW
      CD(M)=FI(M)/AS
      M=M+1
      IF(M-3) 215,216,217
```

```
215 YL=1.0
    FW=FR
    GO TO 211
216 YL=1.5
    GO TO 211
217 IF (M-5) 218,219,220
218 YL=2.0
    GO TO 211
219 YL=POL
    GO TO 211
220 PRINT4, GZ(1),GZ(2),GZ(3),GZ(4),GZ(5)
    PRINT4,GL(1),GL(2),GL(3),GL(4),GL(5)
    PRINT4,FD(1),FD(2),FD(3),FD(4),FD(5)
    PRINT4,FX(1),FX(2),FX(3),FX(4),FX(5)
    PRINT4,FB(1),FB(2),FB(3),FB(4),FB(5)
    PRINT4,FI(1),FI(2),FI(3),FI(4),FI(5)
    PRINT4,CD(1),CD(2),CD(3),CD(4),CD(5)
    PRINT4,EF(1),EF(2),EF(3),EF(4),EF(5)
    PUNCH1,FI(1),FI(2),FI(3),FI(4),FI(5)
    PUNCH1,EP,PN,F,PX,WQ,WT
    PUNCH1,BO,GC,HH,HF,POL,TB
    PUNCH1,SB,RE,T3,HS,FK,FR
    PUNCH1,WO,DD,H,BN,GF,VT
    PUNCH1,SNL,TS,CC,BG,AP,B
    PUNCH1,FQ,TE,BX,FH,XA,WF
    PUNCH1,WN,UY,UZ,EZ,PU,VV
    PUNCH1,PV,HD
    PAUSE
    END
```

```
      DIMENSION PR(5),FI(5),PS(5),G(5),DL(5),PP(5),EX(5),ST(5),VA(5)
      DIMENSION P(5),E(5),PM(5),SP(5)
    1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
    4 FORMAT (F11.3,8X F11.3,F11.3,F11.3,F11.3)
      READ1, FI(1),FI(2),FI(3),FI(4),FI(5)
      READ1, EP,PN,F,PX,WQ,WT
      READ1, BO,GC,HH,HF,POL,TB
      READ1, SB,RE,T3,HS,FK,FR
      READ1, WO,DD,H,BN,GF,VT
      READ1, SNL,TS,CC,BG,AP,B
      READ1, FQ,TE,BX,FH,XA,WF
      READ1, WN,UY,UZ,EZ,PU,VV
      READ1, PV,HD
      FS1=2.0*GC*PN*F
      FS2=2.0*FS1
      M=0
  150 IF(M-1)151,152,178
  151 RM=RE*0.000001
      GO TO 153
  152 RM=RE*(T3+234.5)*0.00000000396
  153 AA=(FS1/RM)**0.5*DD*0.32
      AB=(FS2/RM)**0.5*DD*0.32
      IF(AA-2.5) 160,160,161
  160 V1=1.0-0.15*AA+0.3*AA*AA
      GO TO 162
  161 V1=AA
  162 IF(AB-2.5) 163,163,164
```

```
163 V2=1.0-0.15*AB+0.3*AB*AB
    GO TO 165
164 V2=AB
165 IF(H-B) 167,166,167
166 VC=0.75/V1
    GO TO 169
167 IF(DD) 166,168,166
168 VC=H/(3.0*B*V1)
169 VS=HD/WO+VT+VC
    VG=TB/(CC*GC)
    Q1=1.0-(1.0/(((BO*0.5/GC)**2.0+1.0)**0.5))
    QZ=BO/TS
    Q2=1.05*SIN(QZ*2.844)
    IF(QZ-0.37)170,170,171
170 Q3=0.46
    GO TO 172
171 Q3=0.23*SIN(10.46*QZ-2.1)+0.23
172 Q4=SIN(6.283*TB/TS-1.571)+1.0
    Q5=SIN(12.566*TB/TS-1.571)+1.0
    IF(DD) 174,174,173
173 AB=0.785*DD*DD
    GO TO 175
174 AB=H*B
175 W2=PX*BN*SB*RM*1.246/AB
    W3=(Q2/(2.0*VS+(VG/Q4)))**2.0*V1
    W5=(Q3/(2.0*VS+(VG/Q5)))**2.0*V2
    WD=(TS*BG*Q1*CC)**2.0*W2*(W3+W5)
    M=M+1
```

```
      IF(M-1)176,176,177
  176 WU=WD
  177 GO TO 150
  178 UA=0.0
      M=1
  179 IF(M-1)181,181,182
  181 PW=PU
      FW=FK
      WW=WU
      GO TO 183
  182 PW=PV
      FW=FR
      WW=WD
  183 PR(M)=FI(M)*FI(M)*FW
      PS(M)=PW*UA*UA
      G(M)=(GF*UA)**2.0+1.0
      DL(M)=G(M)*WW
      PP(M)=G(M)*WN
      EX(M)=EZ*PS(M)
      ST(M)=(2.0*(0.0027*XA*UA)**1.8+1.0)*WT
      SP(M)=PP(M)+DL(M)+PR(M)+PS(M)+EX(M)+ST(M)+WF+WQ
      VA(M)=VV*UA
      P(M)=SP(M)+VA(M)
      PM(M)=(SP(M)/P(M))*100.0
      E(M)=100.0-PM(M)
      M=1+M
      IF(M-3)184,185,186
```

```
184 UA=1.0
    GO TO 179
185 UA=1.5
    GO TO 183
186 IF(M-5)187,188,189
187 UA=2.0
    GO TO 183
188 UA=POL
    GO TO 183
189 PRINT4, PR(1),PR(2),PR(3),PR(4),PR(5)
    PRINT4, WF,WF,WF,WF,WF
    PRINT4, ST(1),ST(2),ST(3),ST(4),ST(5)
    PRINT4, WQ,WQ,WQ,WQ,WQ
    PRINT4, PP(1),PP(2),PP(3),PP(4),PP(5)
    PRINT4, DL(1),DL(2),DL(3),DL(4),DL(5)
    PRINT4, PS(1),PS(2),PS(3),PS(4),PS(5)
    PRINT4, EX(1),EX(2),EX(3),EX(4),EX(5)
    PRINT4, SP(1),SP(2),SP(3),SP(4),SP(5)
    PRINT4, VA(1),VA(2),VA(3),VA(4),VA(5)
    PRINT4, P(1),P(2),P(3),P(4),P(5)
    PRINT4,PM(1),PM(2),PM(3),PM(4),PM(5)
    PRINT4, E(1),E(2),E(3),E(4),E(5)
    IF(SNL)191,191,190
190 PUNCH1,FH,TE,BX,UZ,UY,FQ
    PUNCH1,AP,HF,HH,HS,EP
191 PAUSE
    END
```

```
      DIMENSION Q(3),R(58)
    1 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
      READ1, FH,TE,BX,UZ,UY,FQ
      READ1, AP,HF,HH,HS,EP
      READ1, R(1),R(2),R(3),R(4),R(5),R(6)
      READ1, R(7),R(8),R(9),R(10),R(11),R(12)
      READ1, R(13),R(14),R(15),R(16),R(17),R(18)
      READ1, R(19),R(20),R(21),R(22),R(23),R(24)
      READ1, R(25),R(26),R(27),R(28),R(29)
      READ1, R(30),R(31),R(32),R(33),R(34),R(35)
      READ1, R(36),R(37),R(38),R(39),R(40),R(41)
      READ1, R(42),R(43),R(44),R(45),R(46),R(47)
      READ1, R(48),R(49),R(50),R(51),R(52),R(53)
      READ1, R(54),R(55),R(56),R(57),R(58)
      GO TO 234
  228 IF(BF-140.0)230,230,229
  229 IF(J-2)239,241,243
  230 VQ=0.0
  231 RM=R(L)
      L=L+1
      VL=VQ+5.0
      RN=R(L)
      IF(VL-BF)232,232,233
  232 VQ=VL
      GO TO 231
  233 Q(J)=(RN-RM)*(BF-VQ)/5.0+RM
      GO TO (236,237,238),J
```

```
234 UB=0.7
235 UB=UB+0.1
    V=1.732*EP*UB
    FG=FH*UB
    TD=TE*UB
    BC=BX*UB
    J=1
    L=1
    BF=BC
    GO TO 228
236 AT=UZ*Q(J)
    L=1
    J=2
    BF=TD
    GO TO 228
237 FT=Q(J)*HS
    SA=FT+AT
    UX=(FG+SA)*UY
    TF=FQ*UB+UX
    PD=TF/AP
    J=3
    L=30
    BF=PD
    GO TO 228
238 FA=(HF+HH)*Q(J)
    FN=SA+FA
246 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5//)
    PRINT1,V,FG,TD,FT,BC,AT
```

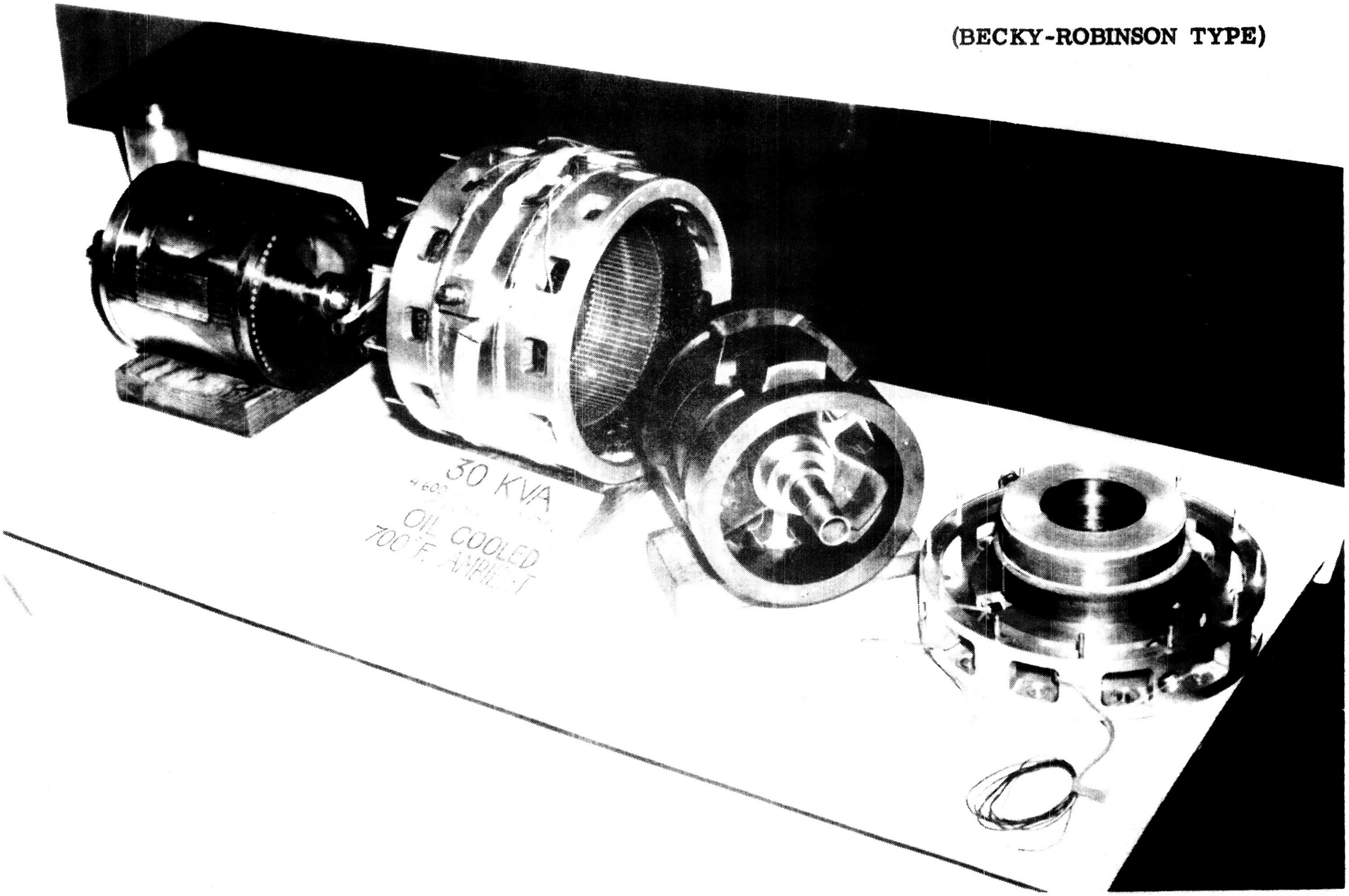
```
      PRINT246,SA,UX,TF,PD,FA,FN
      IF(UB-1.6) 235,245,245
239   PRINT 240
240   FORMAT(23H CORE DENSITY SATURATED)
      GO TO 245
241   PRINT 242
242   FORMAT(24H TOOTH DENSITY SATURATED)
      GO TO 245
243   PRINT 244
244   FORMAT(23H POLE DENSITY SATURATED)
245   PAUSE
      END
```

TWO COIL LUNDELL

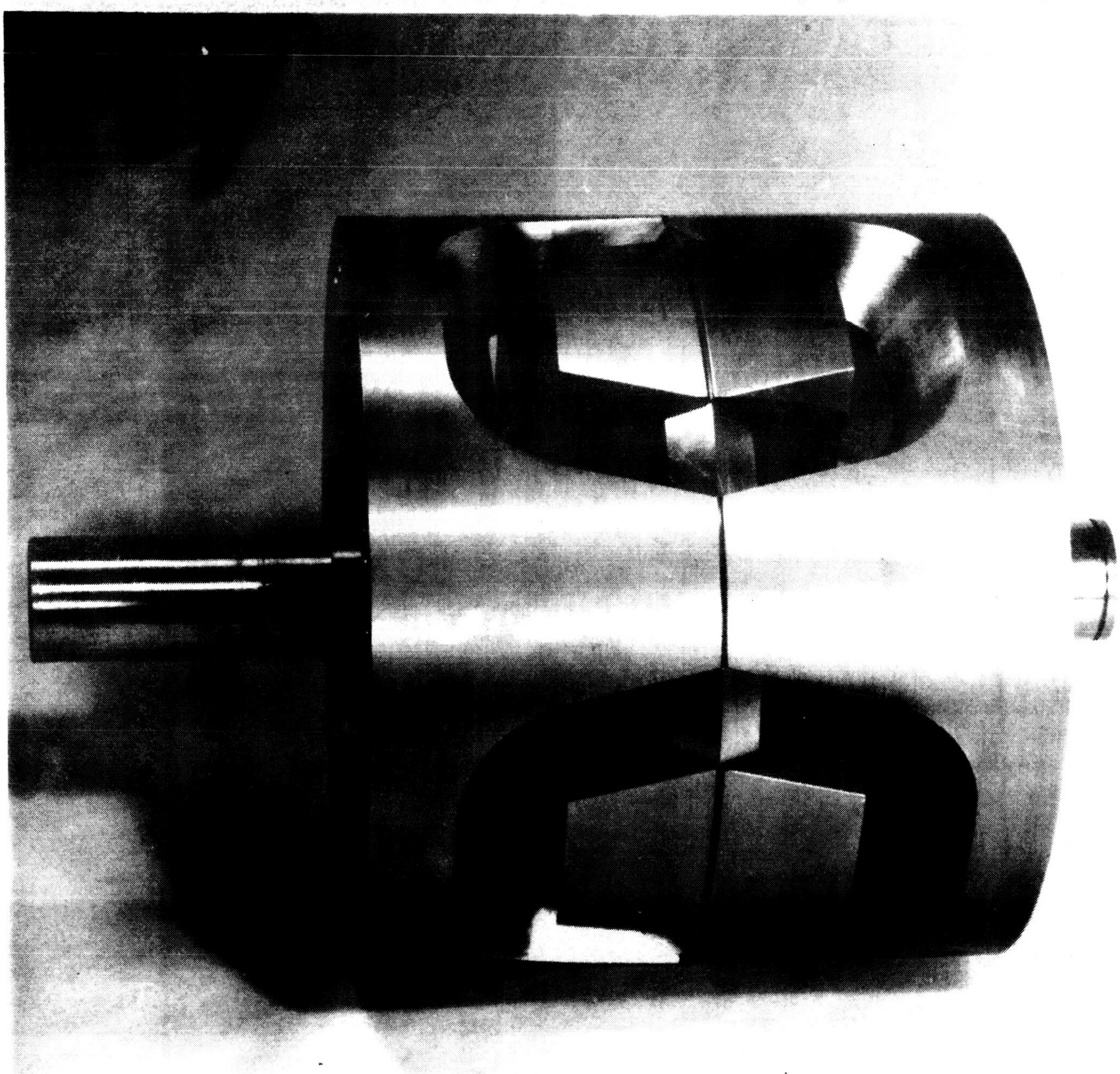
(BECKY-ROBINSON TYPE)

TWO COIL LUNDELL

(BECKY-ROBINSON TYPE)



60 KVA
TWO COIL LUNDELL
(BECKY-ROBINSON TYPE)
ROTOR



LUNDELL GENERATOR
SALIENT POLE SYNCHRONOUS DESIGN SHEET

STATOR

Punching I.D. ____
Punching O.D. ____
Core Length ____
DBS x 2 ____
Slots ____
Size Slots ____
Carter Coeff. ____

Type Wdg. ____
Throw ____
Skew & Dist. Fact. ____
Chord Fact. ____
Cond. Per Slot ____
Total Eff. Cond. ____
Cond. Size ____
Cond. Area ____
Current Density ____

Wdg. Const. ____ Ci ____
Total Flux ____
Gap Area ____
Gap Density ____
Pole Const. ____
Flux Per Pole ____

Tooth Pitch ____
Tooth Density ____
Core Density ____
Grade Of Iron ____

1/2 Mean Turn ____
Res. Per Ph. At ____ ° ____
Eddy Fact. Top ____
Eddy Fact. Bottom ____

Demag. Fact. Cm ____ Cq ____
Amp. Cond. Per In. ____
React. Factor ____
Cond. Perm. ____
End Perm. ____
Leakage React. ____
Air Gap Perm. ____
React. Of Arm. Xad ____ Xaq ____

Wt. Of Copper ____
Wt. Of Iron ____

ROTOR

Single Gap ____ ge ____
Rotor Diameter ____
Peripheral Speed ____
Pole Pitch ____ α ____
Pole Area ____
P_1 ____ P_5 ____
P_2 ____ P_6 ____
P_3 ____ P_7 ____
P_4 ____ ____
Grade Of Iron ____

No. Damper Bars ____
Bar Size ____
Bar Pitch ____ h_o ____ b_o ____

Turns Per Pole ____
Cond. Size ____
Cond. Area ____
Mean Turn ____
Res. At ____ °

Wt. Of Copper ____
Wt. Of Iron ____

% Load			
Amps.			
Volts			
Amps/In.^{2}			

Field Leak. React. ____
Field Self Induct. ____
Damp. Leak. XDd ____ XDq ____

REACT.-TIME CONST.

Synch. Xd ____ Xq ____
Unsat. Trans. ____
Sat. Trans. ____
Subtrans. X''_d ____ X''_q ____
Neg. Sequence ____
Zero Sequence ____
Open Circ. Time Con. ____
Arm. Time Con. ____
Trans. Time Con. ____
Subtrans. Time Con. ____

SATURATION

Air Gap A.T. ____
Stator A.T. ____
Pole A.T. ____
No Load A.T. ____
Rated Load A.T. ____
Overload A.T. ____
Short Circ. A.T. ____
Short Circ. Ratio ____

LOSSES-EFFICIENCY

% Load			
F & W			
Sta. Teeth			
Sta. Core			
Pole Face			
Damper			
Sta. I^2R			
Eddy			
Rot. I^2R			
Σ Losses			
Rating			
Rtg.+Loss			
% Loss			
% Eff.			

Stator Watts/In.^{2} ____
Rotor Watts/In.^{2} ____

E.W.O. ____ Model No. ____ Type Cooling ____

____ KVA ____ % PF ____ Volts ____ Amps. ____ Ph. ____ Cycles ____ RPM

Designed By ____ Date ____

STATOR

PUNCHING I. D. --(d) The inside diameter of the stator punchings.

PUNCHING O. D. --(D) The outside diameter of the stator punchings.

CORE LENGTH--(ℓ) The overall length of the stator iron. Also record on this line the solid core length (ℓ_s). The solid length is the overall length times the stacking factor (K_i). The stacking factor allows for the coating on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in the table below.

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K_i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

If ventilating ducts are used their length must be subtracted from the overall length also.

DEPTH BELOW SLOTS x 2--($2h_c$) The depth of the stator core below the slots times 2.

$$2h_c = D - (d+2h_s)$$

Due to mechanical strength reasons h_c should never be less than 70% of h_s.

SLOTS--(Q) The number of stator slots. Write Q as a product of poles (p) times phases (m) times slots per phase per pole (q). Thus pmq = Q. In general fractions of q close to 1/3 and 2/3 should be avoided, because these fractions are inclined toward producing force poles that cause excessive noise and vibration. In three phase machines fractions of q with thirds or any multiple of three in the denominator should be avoided because with these values a balanced winding cannot be obtained.

SIZE SLOTS--(b_s and h_s) The width of the stator slot (b_s) and the depth of the stator slot (h_s).

CARTER COEFFICIENT--(K_s) The Carter coefficient for the stator slots.

$$K_s = \frac{\tau_s(5g+b_s)}{\tau_s(5g+b_s)-b_s^2} \quad \text{(for open slots)}$$

$$K_s = \frac{\tau_s(4.44g+.75b_o)}{\tau_s(4.44g+.75b_o)-b_o^2} \quad \text{(for partially closed slots)}$$

TYPE WINDING-- Record whether star or delta (Y or Δ), and whether series or parallel.

THROW--(y) The coil span in slots. Record the percent span (y/mq) and designate the slots in which the coil is placed (1 + y).

SKEW AND DISTRIBUTION FACTORS--(K_{sk} and K_d) The skew factor (K_{sk}) is the ratio of the voltage induced in the coils to the voltage that sould be induced if there was no skew.

OR
$$K_{sk} = \frac{\sin \frac{\tau_{sk}\pi}{2\tau_p}}{\frac{\tau_{sk}\pi}{2\tau_p}}$$

The distribution factor (K_d) is the ratio of the voltage induced in the coils to the voltage that would be induced if the winding was concentrated in a single slot

$$K_d = \frac{\sin(q\alpha_{s/2})}{q \sin\alpha_{s/2}} \quad \text{(for integral slot machines)}$$

$$K_d = \frac{\sin(N\alpha\, m/2)}{N \sin\alpha\, m/2} \quad \text{(for fractional slot machines)}$$

See table 2 for a compilation of distribution factors for the various harmonics. See "Grouping of Fractional Slot Windings" and "Distribution Factor" sections of the APPENDIX for an explanation of K_d for fractional slot machines.

CHORD FACTOR--(K_p) The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil.

$$K_p = \sin\left(\frac{Y}{mq} \times 90^{\circ}\right)$$

See Table 1 for a compilation of the pitch factors for the various harmonics.

CONDUCTORS PER SLOT--(n_s) The actual number of conductors per slot. For random wound slots use a space factor of 80% to 85% when determining the permissable number.

TOTAL EFFECTIVE CONDUCTORS--(n_e) The actual number of effective series conductors in the stator winding taking into account the chord and skew factors but not allowing for the distribution factor.

$$n_e = \frac{Qn_s K_p K_{sk}}{C}$$

CONDUCTOR SIZE-- Record the number of strands making up each conductor and their bare and insulated sizes. Indicate also the type of strand insulation.

CONDUCTOR AREA--(a_c) The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii.

$$a_c = (\text{width of cond.})x(\text{thickness of cond.}) - .858r_c^2$$

Corner Radii			
Thickness	Width		
	.751 & Up	.187 - .750	Up to .188
.689 & up	3/16	3/16	--
.688 - .439	1/8	3/32	--
.438 - .226	3/32	1/16	--
.225 - .166	1/16	3/64	3/64
.165 - .126	1/16	1/32	1/32
.125 - .073	Rounded edge	1/32	1/64
.072 - .051	Rounded edge	Rounded edge	1/64
.050 & under	Rounded edge	Rounded edge	Rounded edge

Corner	$.858r_c^2$
1/64	.00021
1/32	.00084
3/64	.00189
1/16	.00335
3/32	.00754
1/8	.0134
3/16	.0302

Square wire .072 and under has a radius of .012. A rounded edge is produced by rolling round wire to the specified size.

CURRENT DENSITY--(s) The amperes per square inch of conductor.

$$s = \frac{I_{ph}}{Ca_c}$$

WINDING CONSTANT--(C_w) The ratio of the RMS line voltage for a full pitched winding to that which would be introduced in all the conductors in series if the density were uniform and equal to the maximum value.

$$C_w = \frac{EC_1K_d}{\sqrt{2}E_{ph}m}$$

Assuming $K_d = .955$, $C_w = .225\, C_1$ for three phase delta machines and $C_w = .390C_1$ for three phase star ones. C_1 is the ratio of the maximum fundamental of the field form to the actual maximum of the field form. For pole heads with more than one radius the field form is determined from a flux plot of the air gap flux at no load, neglecting saturation, and C_1 is then obtained by Fourier analysis. For pole heads with only one radius, C_1 is obtained from curve #4. The graphical flux plotting method of determining C_1 is explained in the section titled "Derivations."

TOTAL FLUX--(ϕ_T) The total flux that would exist in the gap if the density was uniform and equal to the maximum gap density.

$$\phi_T = \frac{6000E10^6}{C_w n_e RPM}$$

GAP AREA-- The area of the gap surface at the stator bore $= \pi d \ell$

GAP DENSITY--(B_g) The maximum flux density in the air gap.

$$B_g = \frac{\phi_T}{\pi d \ell}$$

POLE CONSTANT--(C_p) The ratio of the average to the maximum value of the field form. For pole heads with more than one radius C_p is calculated from the same field form that was used to determine C_1, and this method is described in the second part of the manual. For pole heads with only one radius C_p is obtained from curve #4. Note the correction factor at the top of the curve.

FLUX PER POLE--(ϕ_p) The total flux per pole.

$$\phi_p = \frac{\phi_T C_p}{p}$$

TOOTH PITCH--(τ_s and $\tau_{s\frac{1}{3}}$) The stator slot pitch on the inside stator bore, and the stator slot pitch at a distance a third of the way up the tooth.

$$\tau_s = \frac{\pi d}{Q} \qquad \tau_s 1/3 = \frac{\pi(d + \frac{2}{3} h_s)}{Q}$$

TOOTH DENSITY--(B_t) The flux density in the stator tooth at 1/3 of the distance from the minimum section.

$$B_t = \frac{\phi_T}{Q \ell_s b_{t\,1/3}} \quad \text{where } b_{t\,1/3} = \tau_{s\,1/3} - b_s$$

CORE DENSITY--(B_c) The flux density in the stator core, without adding the stator to rotor leakage flux.

$$B_c = \frac{\phi_p}{2h_c\ell_s}$$

GRADE OF IRON-- Alloy identification and lamination thickness of stator iron.

1/2 MEAN TURN--(ℓ_t) The average length of one conductor.

$$\ell_t = \ell + L_E$$

where L_E = the end extension length

For random wound coils

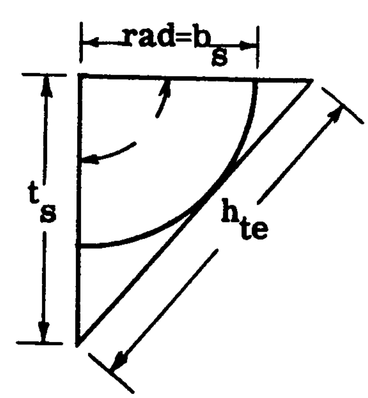
$$L_E = .5 + \frac{K_t \pi y(d+h_s)}{Q}$$

where K_t = constant depending on the number of poles

K_t = 1.3 for 2 poles; 1.5 for 4 poles; and 1.7 for 6 poles and up

For formed coils

$$L_E = 2\ell_{e2} + \pi\left(\frac{h_1}{2} + d_b\right) + yh_{te}$$



where d_b = diameter of bender pin

h_{te} = is obtained from the diagram as shown

ℓ_{e2} = straight part of the coil extension beyond the core

RESISTANCE PER PHASE AT__^{o}--(R_{ph}) The resistance per phase calculated at the expected coil temperature.

$$R_{ph} = \frac{n_s Q \ell_t R_{1000}}{12000\, C^2 m} \times \frac{235 + X^{o}C}{260} = \rho \frac{n_s Q \ell_t}{m a_c C^2}$$

where ρ = resistivity at $X^{o}C$ = $.91 \times 10^{-6}$ $100^{o}C$

R_{1000} = resistance per 1000 ft. of conductor at $25^{o}C$

$X^{o}C$ = expected coil temperature in ^{o}C

EDDY FACTOR TOP-- The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine.

$$EF\,Top = 1 + \left[.584 + \left(\frac{N_{st}^2 - 1}{16}\right)\left(\frac{h'_{st}\ell}{h_{st}\ell_t}\right)^2\right]\frac{3.35}{1000}\left[\frac{h_{st} n_s f a_c}{b_s \rho'}\right]^2$$

where $\rho' = \rho \times 10^6$

N_{st} = number of strands per conductor in depth

h'_{st} = distance between centerline of strands in depth

h_{st} = height of uninsulated strand

EDDY FACTOR BOTTOM-- The eddy factor of the bottom coil at the expected operating temperature of the machine. Use same equation as E. F. top except use .0833 in place of .584.

DEMAGNETIZING FACTOR--(C_M and C_q) The ratio of the field ampere turns to the maximum sine wave stator ampere turns required to force the same fundamental flux across the gap. The demagnetizing factor in the direct axis is

$$C_M = \frac{\alpha\pi + \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

and the cross magnetizing factor in the quadrature axis is

$$C_q = \frac{1/2\cos\frac{\alpha\pi}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

The above factors can be read directly from curve #9 and calculation by the above formulas is thus unnecessary.

AMPERE CONDUCTORS PER INCH--(A) The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. Its value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones.

$$A = \frac{I_{ph} n_s K_p}{C t_s}$$

REACTANCE FACTOR--(X) The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance It is the percent reactance for unit specific permeance, or the percent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current. Specific permeance is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100AK_d}{\sqrt{2}\,C_1 B_g}$$

CONDUCTOR PERMEANCE--(λ_i) The specific permeance for the portion of the stator current that is embedded in the iron. This permeance depends upon the configuration of the slot.

(a) For open slots.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right] \qquad b_t = \text{tooth width at gap}$$

(b) For partially closed slots with constant slot width.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_o}{b_o} + \frac{2h_t}{b_o + b_s} + \frac{h_w}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right]$$

(c) For partially closed slots with constant tooth width.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_o}{b_o} + \frac{2h_t}{b_o + b_1} + \frac{2h_w}{b_1 + b_2} + \frac{h_1}{3b_2} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right]$$

(d) For round slots.

$$\lambda_i = C_X \frac{20}{mq}\left[.62 + \frac{h_o}{b_o}\right]$$

(e) For open slots with a winding of one conductor per slot.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_2}{b_s} + \frac{h_1}{3b_s} + .6 + \frac{g}{2t_s} + \frac{t_s}{4g}\right] \qquad \left(C_X = \frac{1}{K_p^2 K_d^2}\right) \quad (K_X = 1)$$

In all of the above formulas C_X is a reduction factor that is dependent upon the pitch and distribution of the winding.

$$C_X = \frac{K_X}{K_p^2 K_d^2} \qquad \text{where } K_X = \frac{1}{4}\left(\frac{3y}{mq} + 1\right) \text{for 3 phase}$$

$$K_X = \frac{y}{mq} \quad \text{for 2 phase}$$

Values of C_X versus percent pitch for three phase windings are plotted on Graph #1. These values assume a distribution factor of .955. See Graph #1.

END WINDING PERMEANCE--(λ_E) The specific permeance for the end extension portion of the stator winding.

$$\lambda_E = \frac{6.28}{\ell K_d^2}\left[\frac{\phi_E L_E}{2n}\right] K_E$$

(Obtain the value of $\phi_E L_E$ from Graph #1

$$K_E = \frac{\text{Calculated valve of } L_E}{\text{Value of } L_E \text{ from Graph \#1}} \quad \text{(for machines of } d > 8''\text{)}$$

$$K_E = \sqrt{\frac{\text{Calculated value of } L_E}{\text{Value of } L_E \text{ from Graph \#1}}} \quad \text{(for machines of } d < 8''\text{)}$$

LEAKAGE REACTANCE--($X\ell$) The leakage reactance of the stator for steady state conditions

$$X_\ell = \mathbf{X}(\lambda_i + \lambda_E)$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines.

$$\lambda_B = \frac{.1d}{pg_e}\left[\frac{\sin \frac{3y}{mq} \times 90^\circ}{K_p}\right]$$

$$X_\ell = \mathbf{X}(\lambda_i + \lambda_E + \lambda_B) \qquad \text{where } \lambda_B = 0 \text{ for 3 phase machines.}$$

AIR GAP PERMEANCE--(λ_a) The specific permeance of the air gap.

$$\lambda_a = \frac{6.38d}{pg_e}$$

REACTANCE OF ARMATURE REACTION--(X_{ad} and X_{aq}) The "fictituous reactance" due to armature reaction. In the direct axis

$$X_{ad} = X \lambda_a C_1 C_M$$

and in the quadrature axis

$$X_{aq} = X C_q \lambda_a$$

WEIGHT OF COPPER-- The weight in lbs. of the stator copper.

$$\# = .321\, n_s Q a_c \ell_t$$

WEIGHT OF IRON-- The weight in lbs. of the stator iron.

$$\# = .238 \left[b_{tm} Q \ell_s h_s + \pi (D - h_c) hc\, \ell_s \right]$$

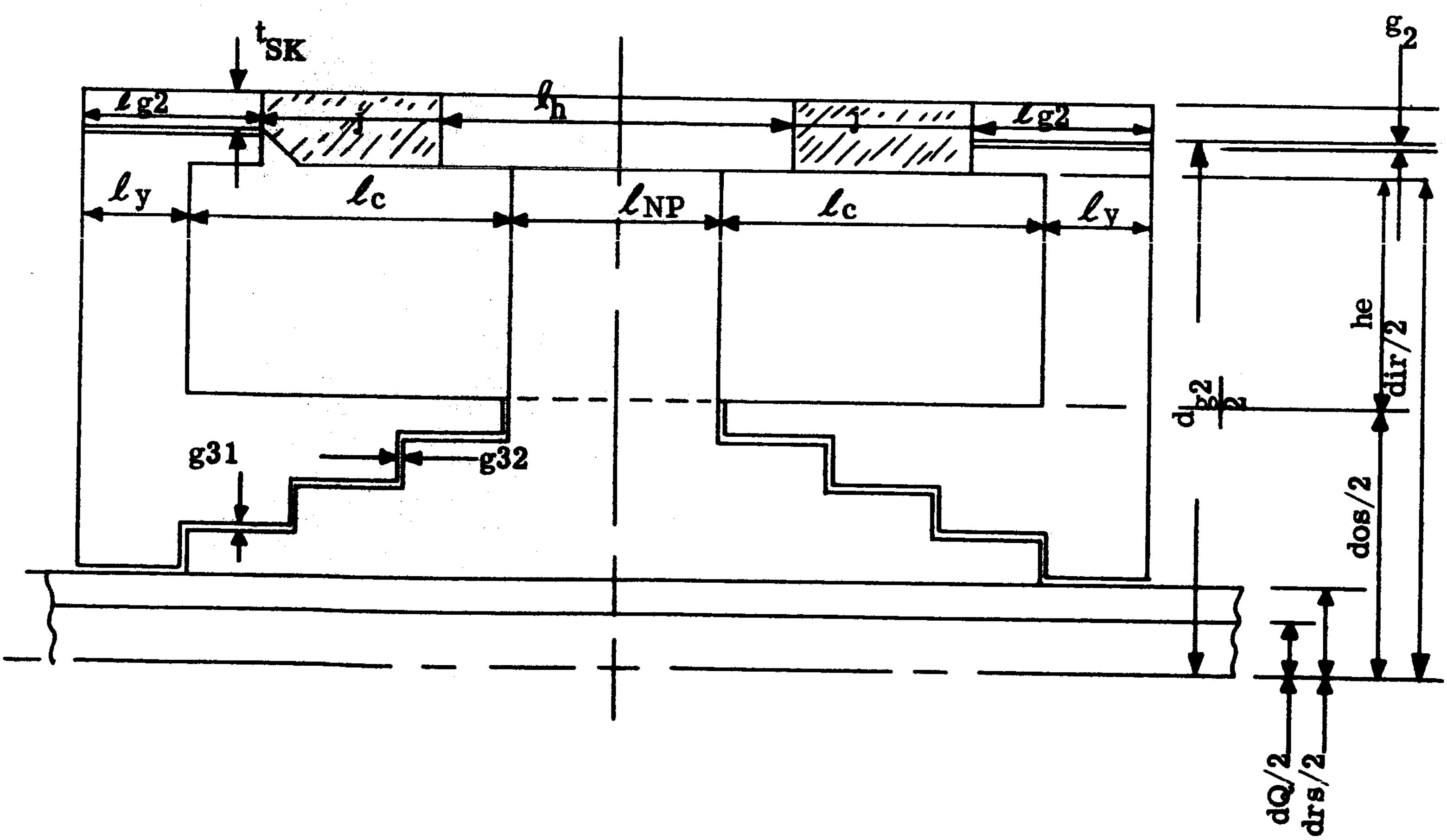
ROTOR

SINGLE GAP--(g) The single air gap. Also record the effective air gap (g_e) inch

$$g_e = K_s g$$

AUXILIARY GAP, OUTER--(g_2) inches

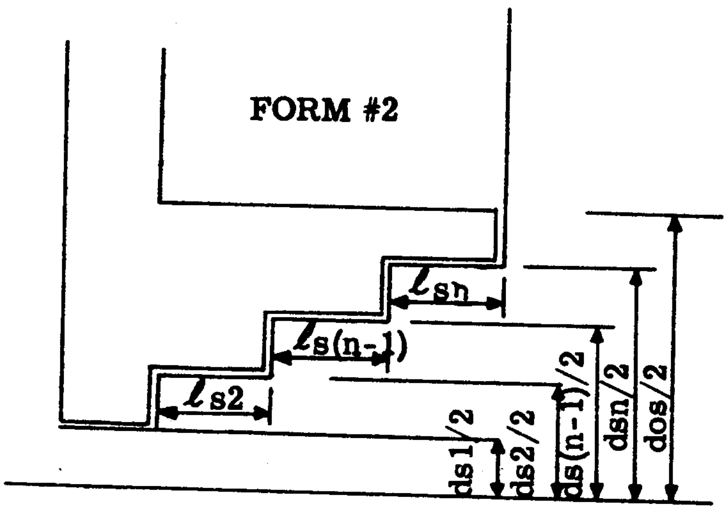
$$g_2 = \text{Obtain length from design layout}$$



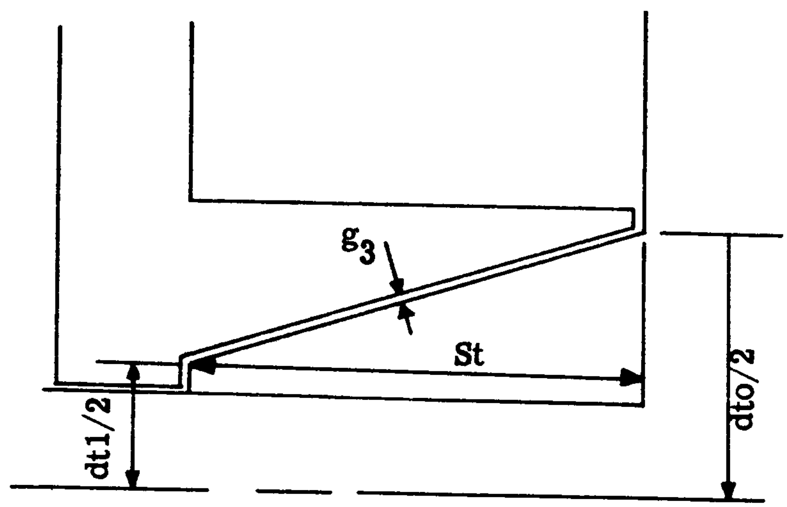
AUXILIARY GAP, INNER--(g_3) inches

g_3 = Obtain length from design layout

STEPPED GAP (g_3)



TAPERED GAP (g_3)



ROTOR DIAMETER--(d_r) The outside diameter of the rotor.

$$d_r = d - 2g$$

PERIPHERAL SPEED--(V_r) The velocity of the rotor surface in feet per minute.

$$V_r = \frac{\pi d_r \, RPM}{12}$$

POLE PITCH--(t_p) The pole pitch measured at the inside diameter of the stator.

$$t_p = \frac{\pi d}{p}$$

Also record the ratio of the pole arc to the pole pitch (α).

$$\alpha = \frac{b_h}{t_p}$$

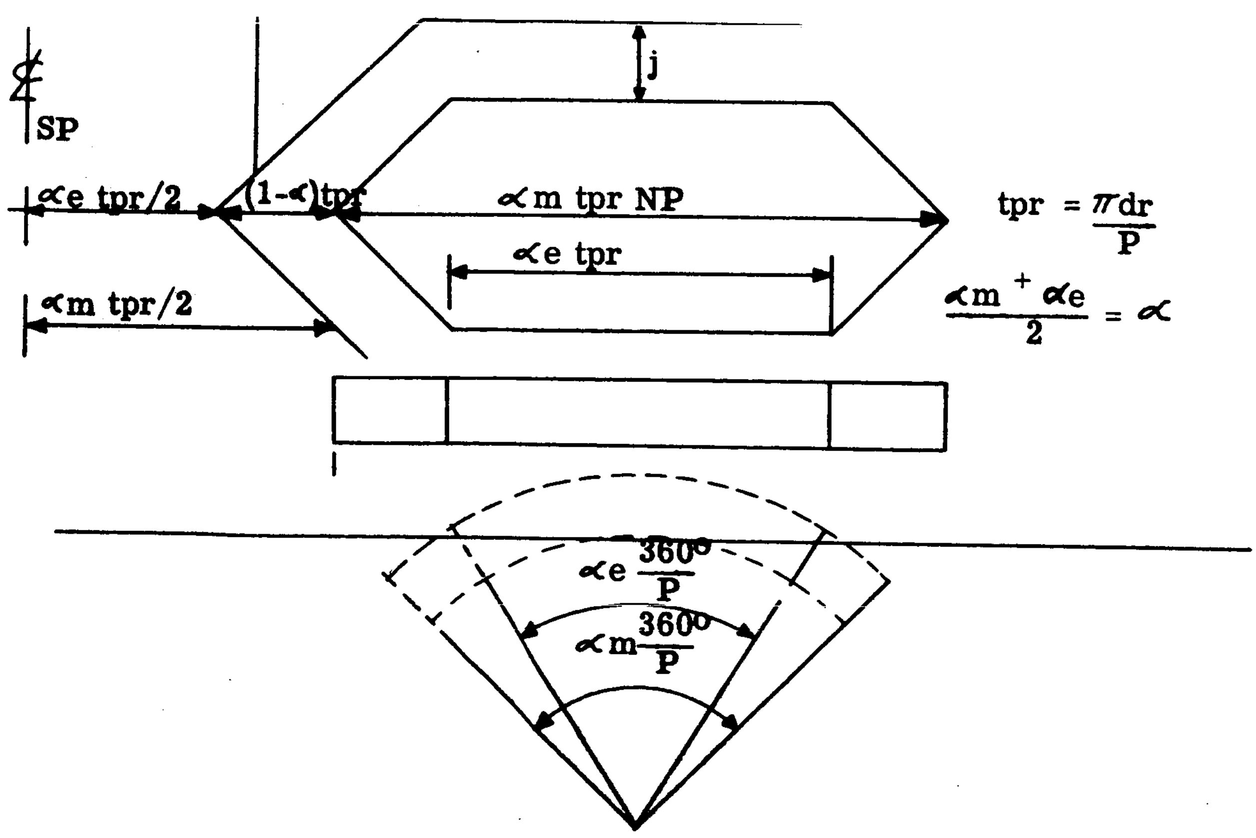
b_h = Average pole head width under stator stack

For pole configuration below

$$\alpha = \frac{\alpha e + \alpha m}{2}$$

αm = Per unit pole embrace (pole middle)

αe = Per unit pole embrace (pole end)

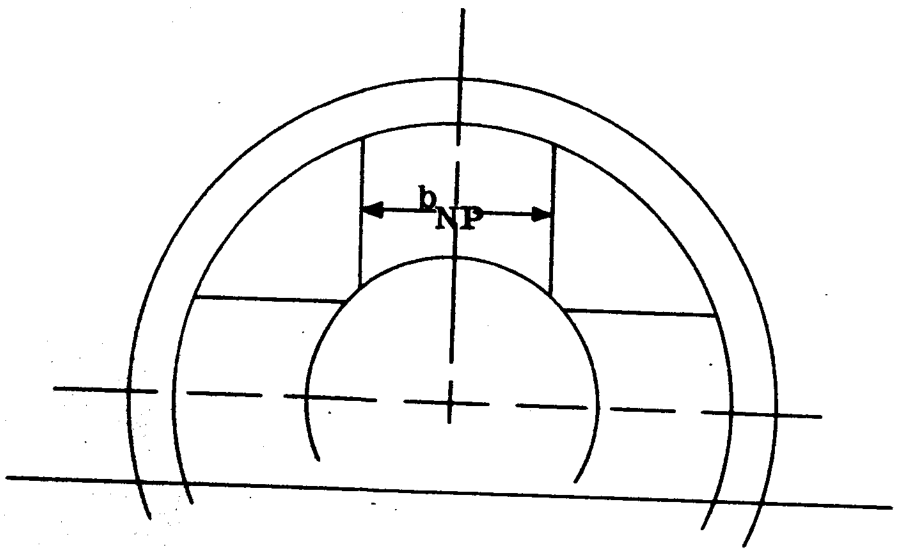


NORTH POLE AREA--(a_{NP}) The effective cross sectional area of the pole.

$$a_{NP} = b_{NP} \ell_p K_i$$

Values of K_i are obtained from chart in Stator Section.

For solid iron $K_i = 1.0$



SOUTH POLE AREA--(a_{SP}) The effective cross sectional area of the south pole at the entry edge of the stator.

$$a_{SP} = b_{SP} t_{SP}$$

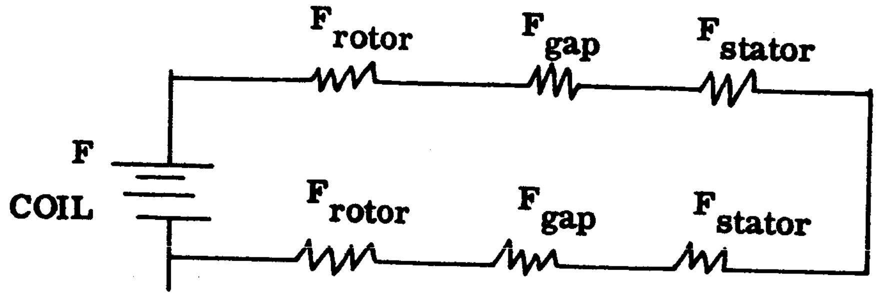
GRADE OF IRON--Alloy of rotor iron and lamination thickness if laminations are used.

TURNS PER COIL--(N_C) The number of field turns per coil.

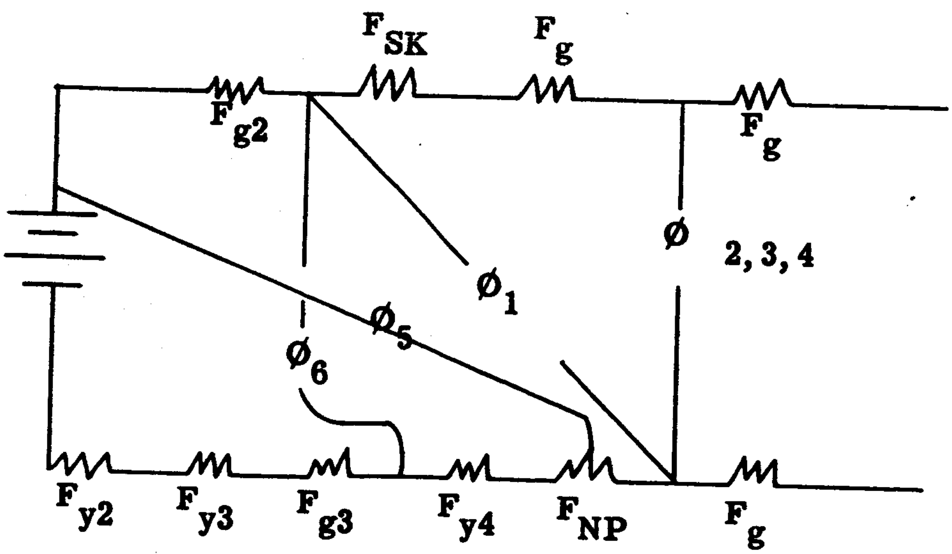
CONDUCTOR SIZE--The bare and insulated sizes of the field conductors. Also indicate the type of insulation.

CONDUCTOR AREA--(a_{cr}) The actual area of the conductor taking into account the corner radius. See stator area of conductor for typical corner radii values.

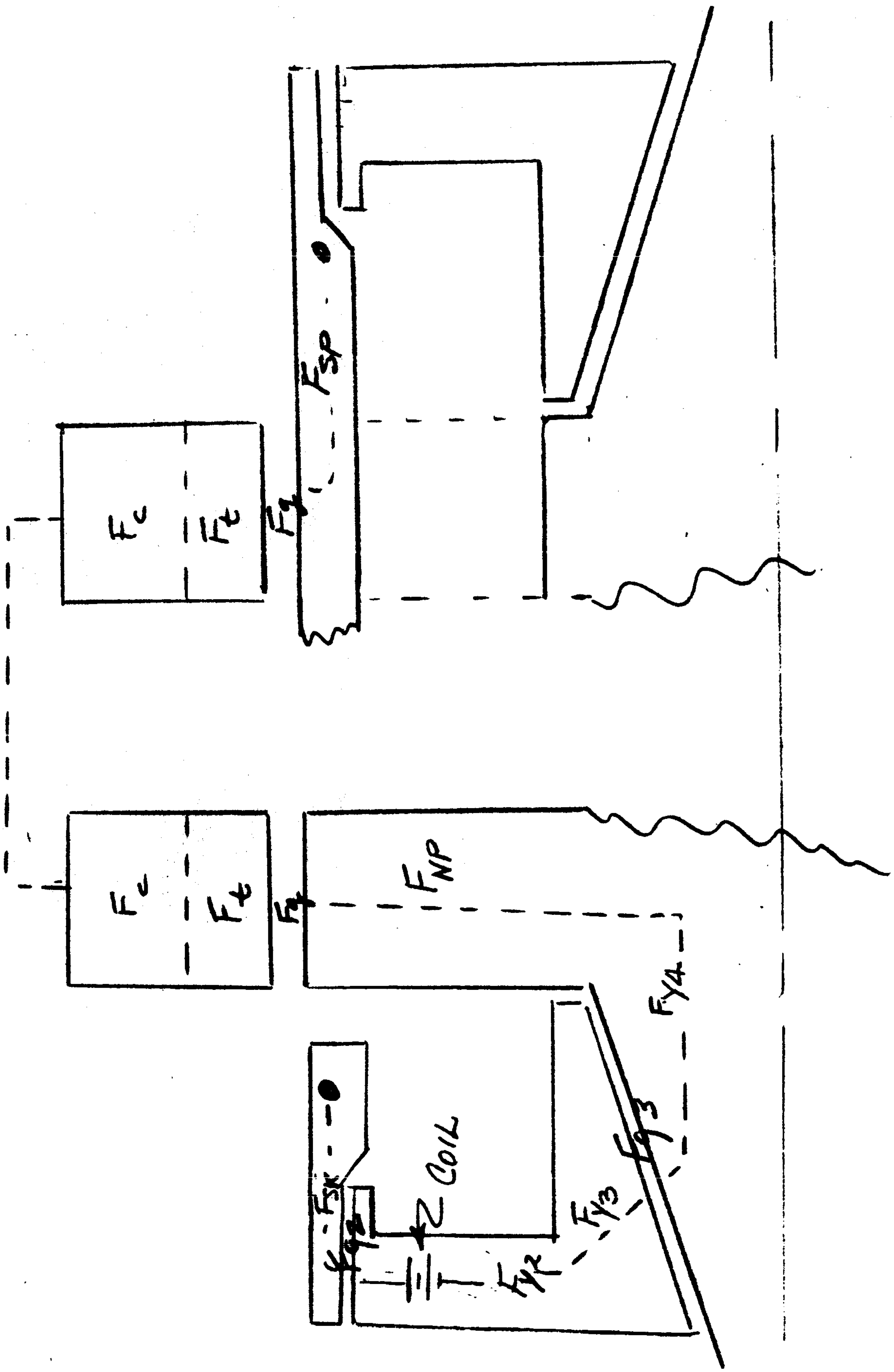
The flux circuit of the two-coil Lundell generator looks like this.



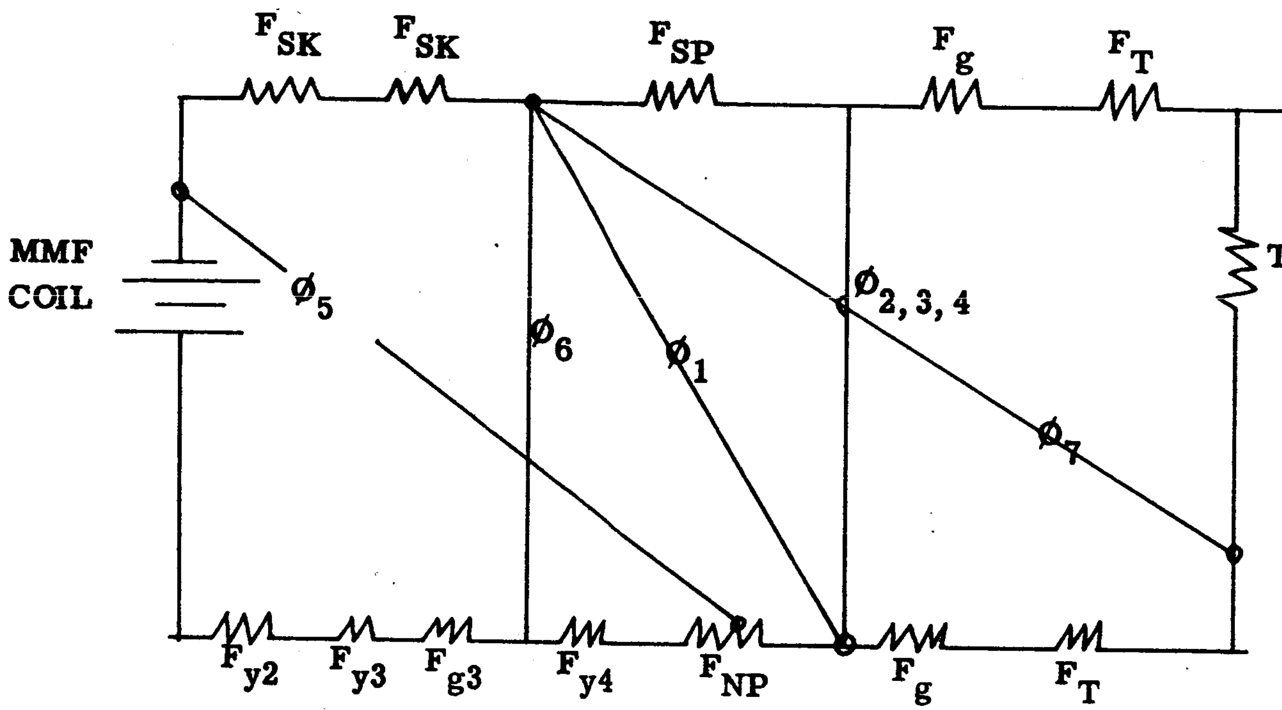
The rotor flux circuit is:



VIEW OF BOTH NORTH-POLE AND SOUTH-POLE FLUX CIRCUITS SHOWING THE MMF DROPS IN THE TWO-COIL LUNDELL BRUSHLESS AC GENERATOR



And for the entire machine, the flux circuit looks like this.



Flux Circuit for 2-Coil Lundell A-C Generator

NOTE: The machine could be represented by showing two identical flux circuits in the south pole, from and including F_{SP} to and including F_{y4}. Instead the calculations are adjusted to fit the single circuit.

The leakage permeances in the flux circuit are:

POLE HEAD END LEAKAGE

$$P_1 = \frac{\mu \text{ Area}}{\ell} = \frac{3.19\ (\tau_P t_{SP})\ (P)}{\ell_1}$$

POLE HEAD SIDE LEAKAGE (P_2)

$$P_2 = \frac{\mu \text{ Area}}{\ell} = \frac{3.19\ (\ell_{NP} + \ell_1)\ t_{SP}\ (P)}{\ell_2}$$

POLE BODY END LEAKAGE (P_3)

$$P_3 = \frac{\mu \text{ Area}}{\ell} = \frac{3.19\ \ell_P\ (h_P - t_{SP})\ P}{(d_r - d_{os})\ \frac{\pi}{8} - t_{SP}}$$

POLE BODY SIDE LEAKAGE

$$P_4 = \frac{\mu \text{ Area}}{\ell} = \frac{3.19 \left[\left(\frac{d_r - d_{os}}{2}\right) - t_{SP}\right]\left((\ell_P + \ell_1)\right) P}{\left(\frac{d_r}{2} - t_{SP}\right) \sin \frac{2\pi}{P}\left[1 - \frac{\alpha}{4}\right] - \frac{b_{NP}}{2}}$$

For six poles and up.

$$P_4 = \frac{3.19 \left[\frac{d_r}{2} - t_{SP}\right]\left(\ell_P + \ell_1\right) P}{\frac{d_r - d_{os}}{2} - t_{SP}}$$

For four pole generators only.

COIL LEAKAGE PERMEANCE TO A NORTH POLE (P_5)

$$P_5 = \frac{\mu \text{Area}}{\ell} = \frac{3.19\, b_P\, (\ell_6)\, \frac{2}{3}\, (2P)}{\ell_c}$$

Obtain ℓ_c from layout.

P_5 = Total leakage permeance for path 5 on both ends of the rotor

COIL LEAKAGE PERMEANCE TO A SOUTH POLE (P_6)

$$P_6 = \frac{\mu \text{Area}}{\ell} = \frac{3.19\, \ell_c\, \alpha (d_r - 2t_{SP})\, \frac{\pi}{P}\, (P)}{\ell_6}$$

= Total leakage permeance for path 6 on both ends of the rotor

$$\ell_6 = \left(\frac{d_r - d_{os}}{2}\right) - t_{SP}$$

STATOR CORE TO ROTOR SKIRT, flux leakage permeance path (P_7)

$$P_7 = \frac{\mu \text{Area}}{\ell}$$

$$\text{Area} = \pi (d_r + h_c)\, \frac{h_c + \ell_{SK}}{2} \ \text{in}^2$$

The leakage is from 1/2 the stator end surface on each side of the stator, making the total leakage surface calculated above.

However - 1/2 of the leakage flux is useful and generates voltage in the stator conductors. So for tooth density, pole density and air-gap flux calculations the leakage flux area is

$$\text{Area} = \frac{1}{2}\,\pi(d_r + h_c)\,\frac{h_c + \ell_{SK}}{2}$$

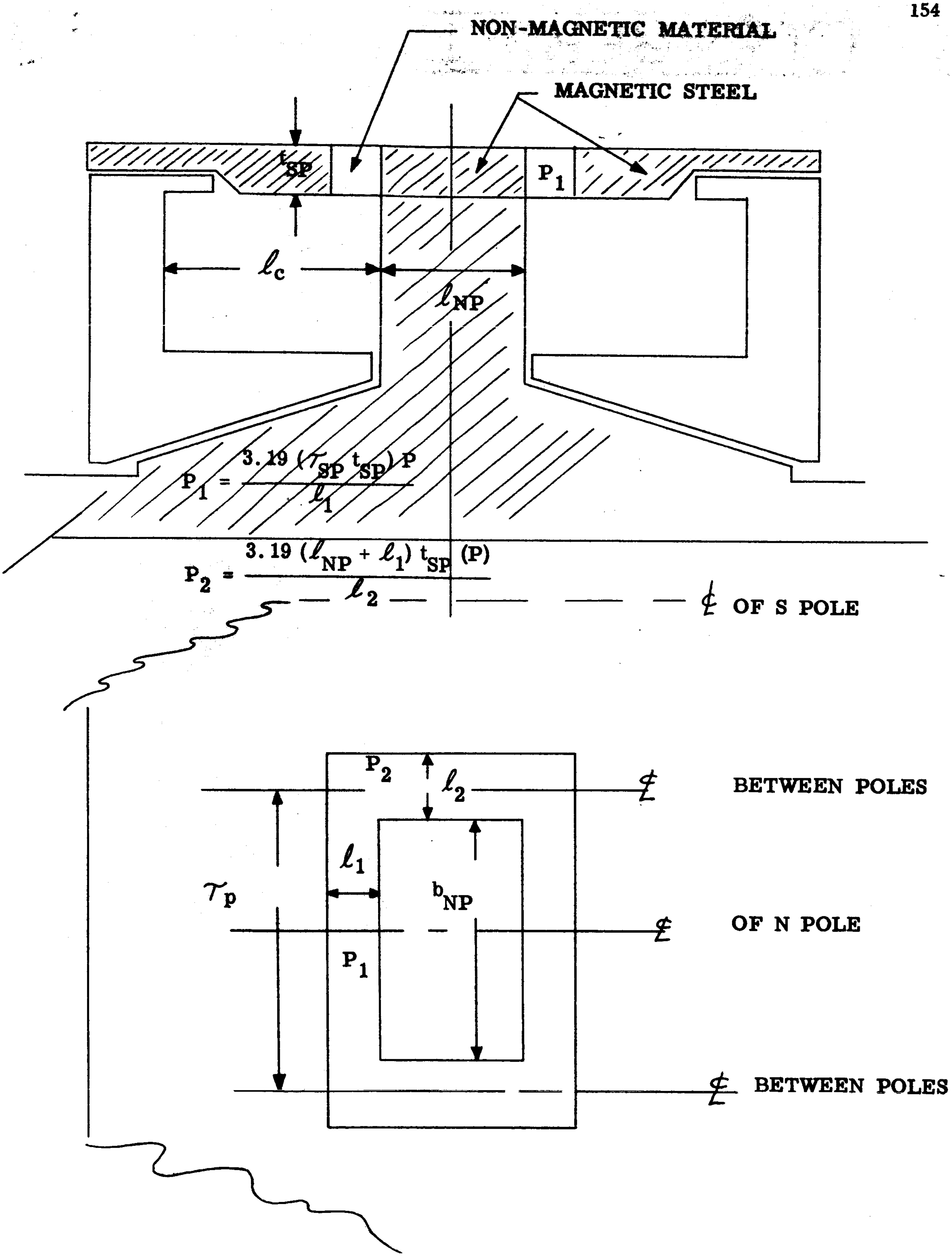
$$= \frac{\pi}{4}\,(d_r + h_c)\,(h_c + \ell_{SK})$$

$$\text{Length} = \pi\frac{h_c}{2}\ \text{inches}$$

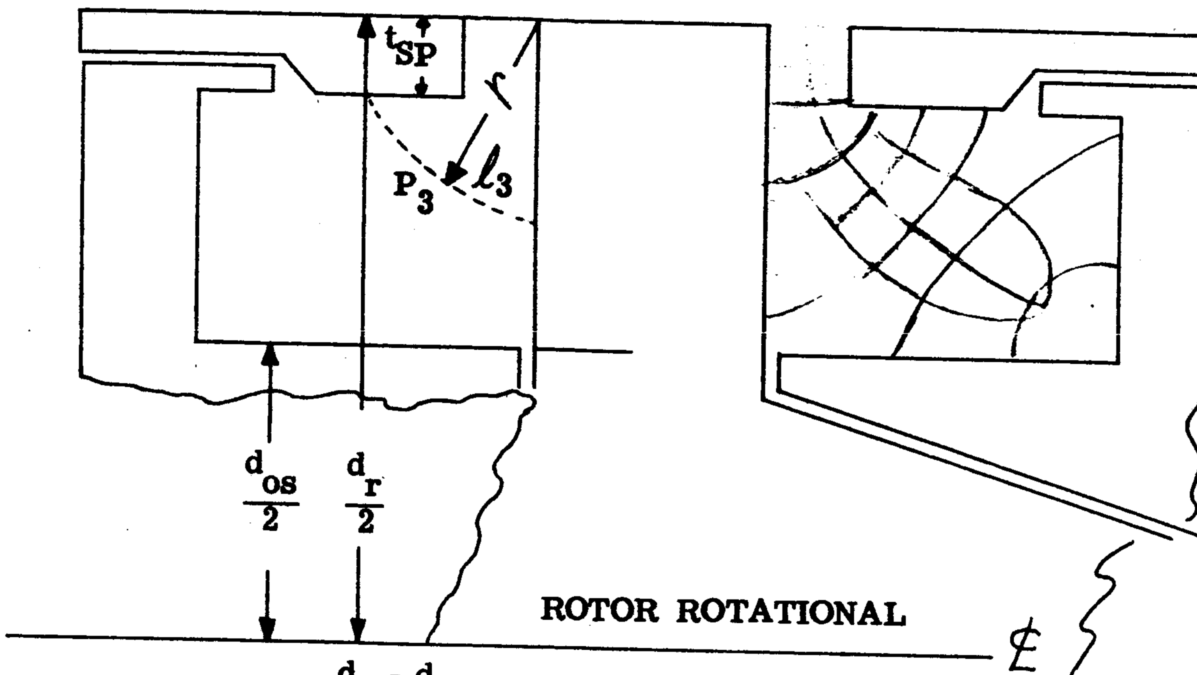
h_c = stator height from bore to back-iron surface, inches

$$P_7 = \frac{3.19\,\frac{\pi}{4}\,(d_r + h_c)\,(h_c + \ell_{SK})}{\pi\,\frac{h_c}{2}\qquad 2}$$

$$= \frac{3.19\,(d_r + h_c)\,(h_c + \ell_{SK})}{2h_c}$$



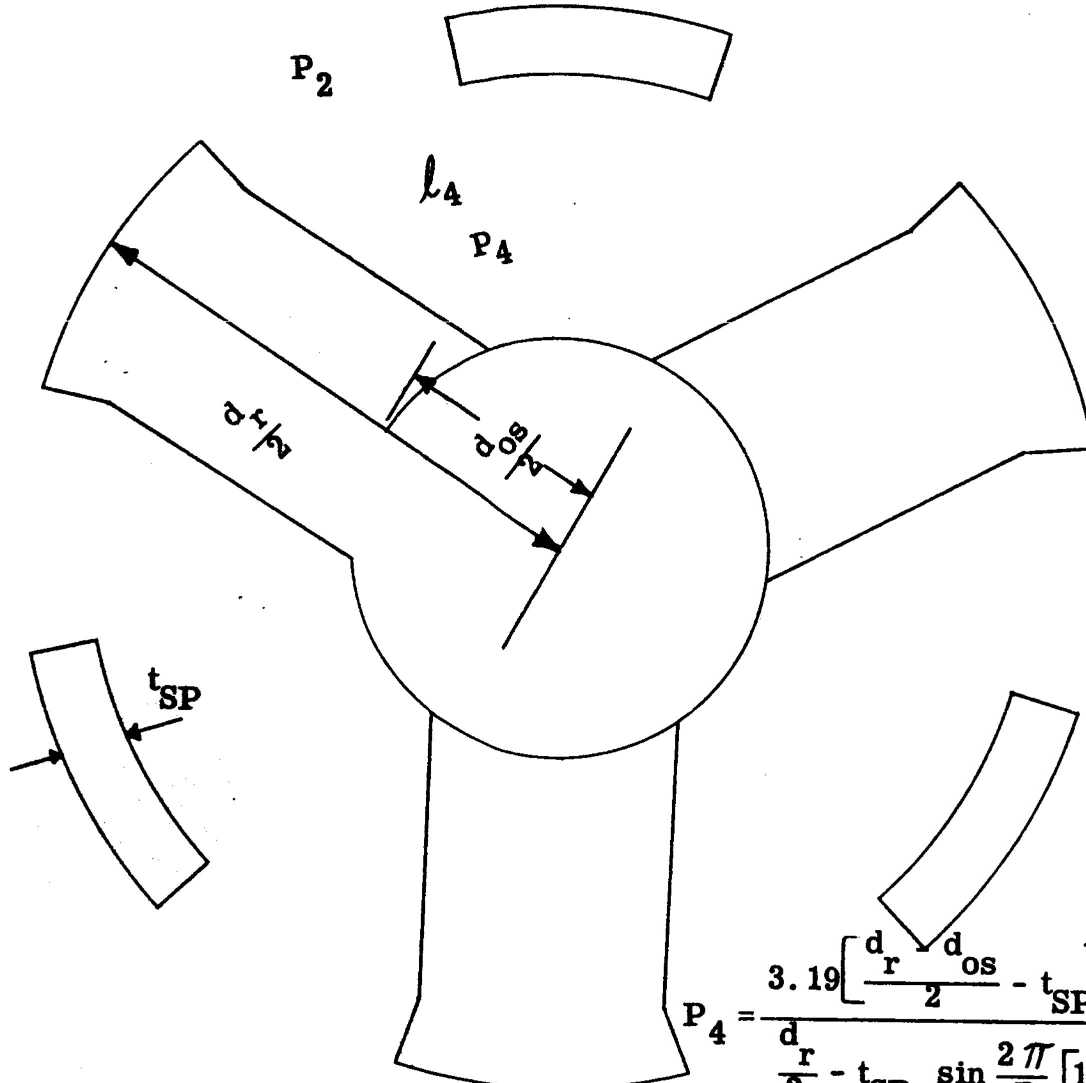
NON-MAGNETIC MATERIAL
MAGNETIC STEEL
t_{SP}
P_1
ℓ_c
ℓ_{NP}
$P_1 = \frac{3.19\,(\tau_{SP}\,t_{SP})\,P}{\ell_1}$
$P_2 = \frac{3.19\,(\ell_{NP} + \ell_1)\,t_{SP}\,(P)}{\ell_2}$
℄ OF S POLE
P_2
ℓ_2
℄ BETWEEN POLES
ℓ_1
τ_p
b_{NP}
℄ OF N POLE
P_1
℄ BETWEEN POLES



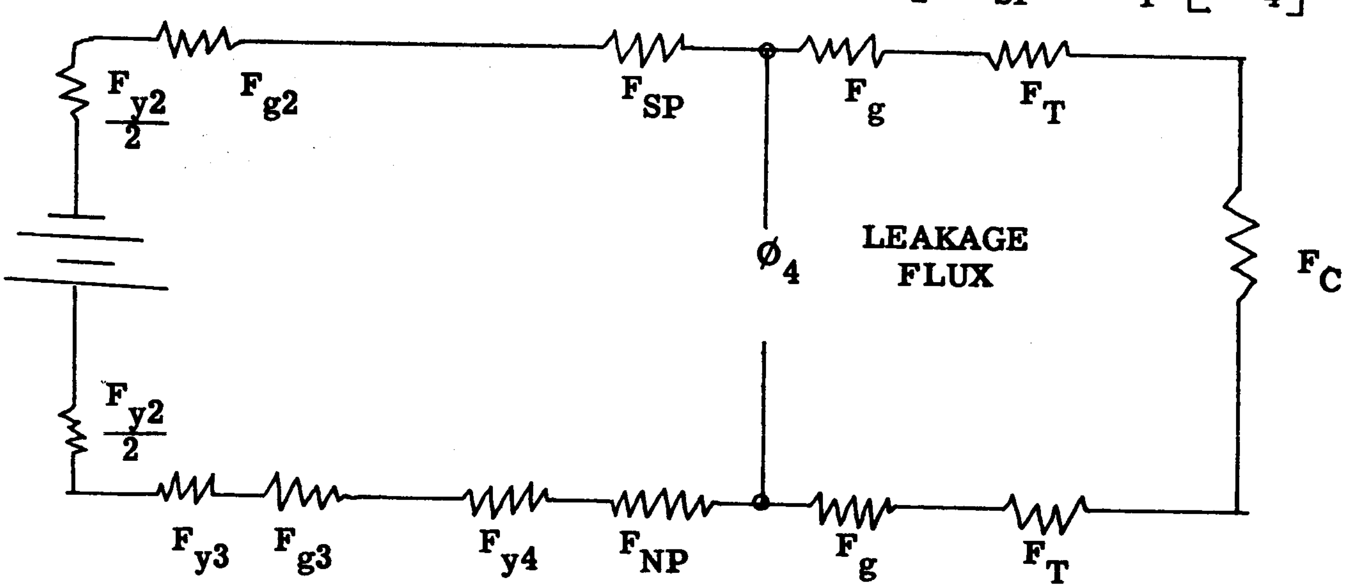
$$r \text{ above} = \frac{d_r - d_{os}}{4}$$

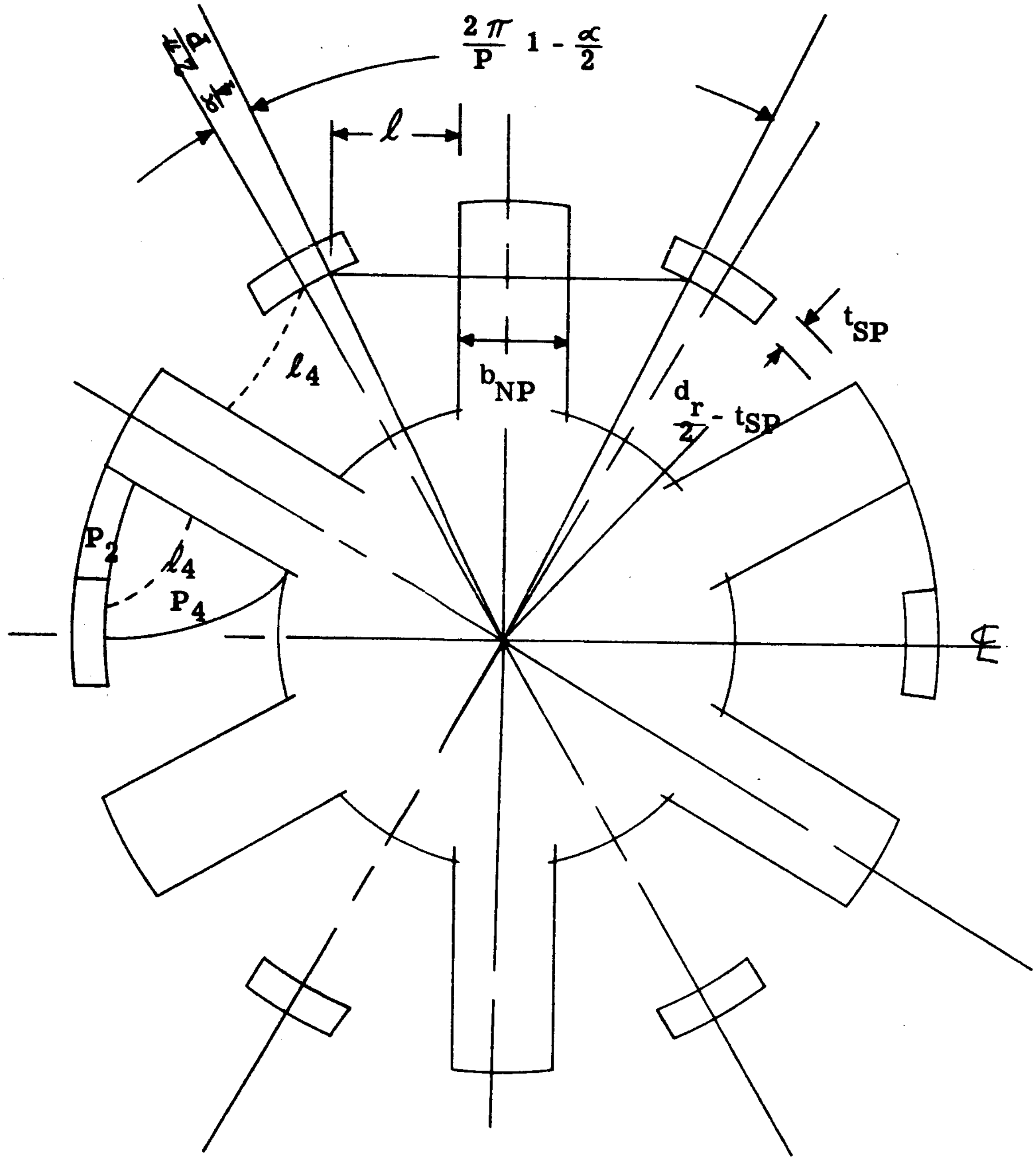
$$\ell_3 = \left(\frac{d_r - d_{os}}{4}\,\frac{\pi}{2}\right) - t_{SP} = (d_r - d_{os})\,\frac{\pi}{8} - t_{SP}$$

$$P_3 = \frac{3.19\,\ell_P\,(h_P - t_{SP})\,P}{\ell_3}$$



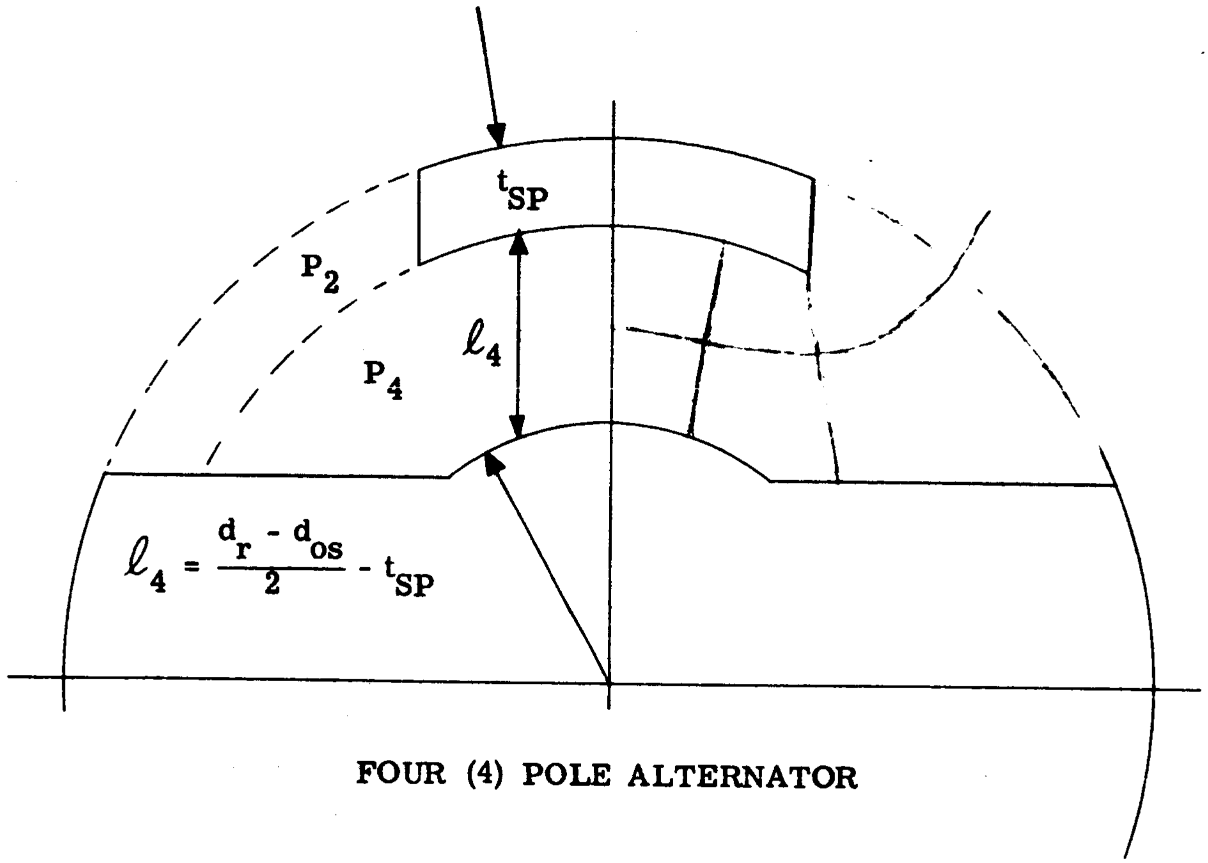
$$P_4 = \frac{3.19\left[\frac{d_r - d_{os}}{2} - t_{SP}\right](\ell_P + \ell_1)\,P}{\frac{d_r}{2} - t_{SP}\ \sin\frac{2\pi}{P}\left[1 - \frac{\alpha}{4}\right] - \frac{b_{NP}}{2}}$$



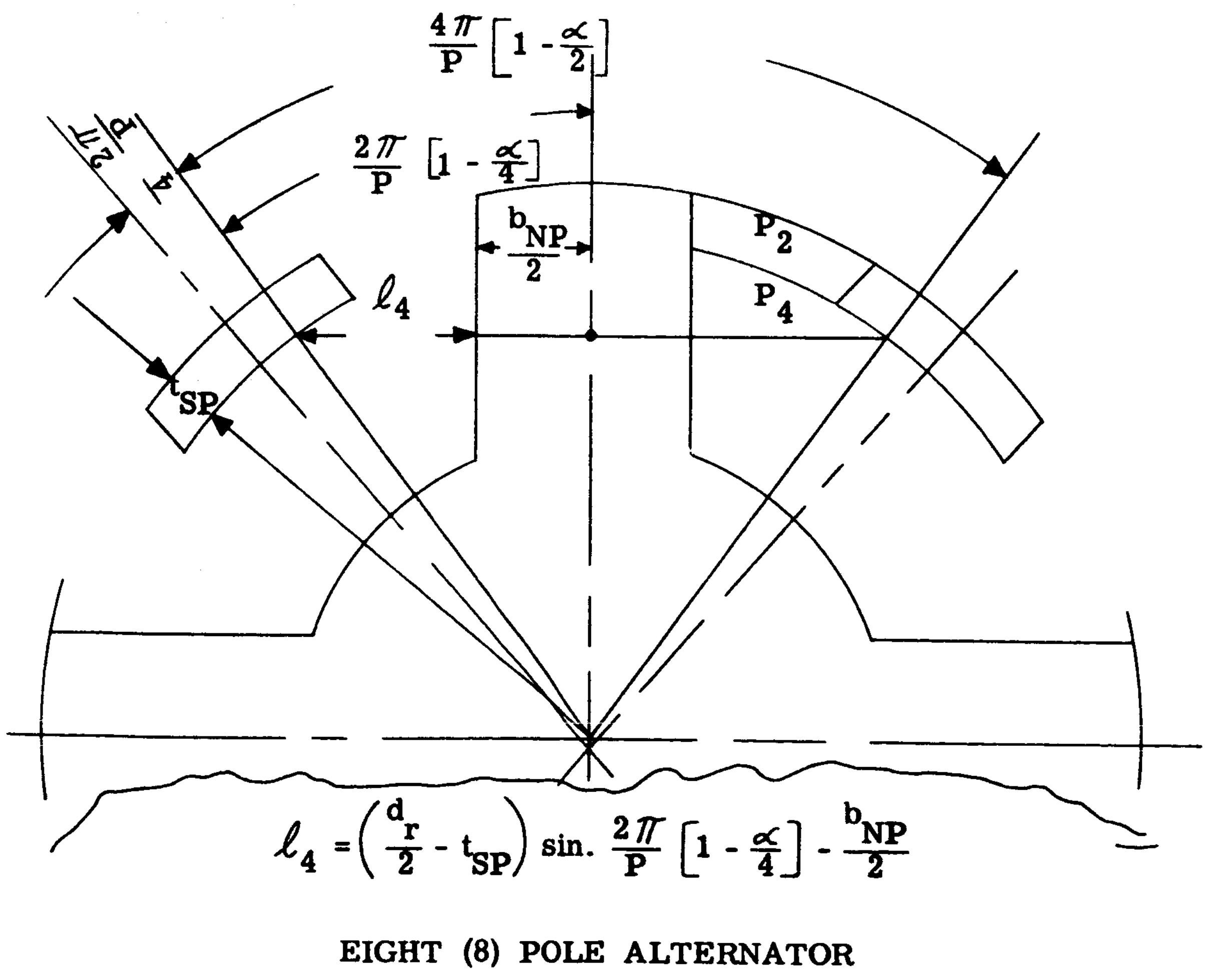


TWELVE (12) POLE ALTERNATOR

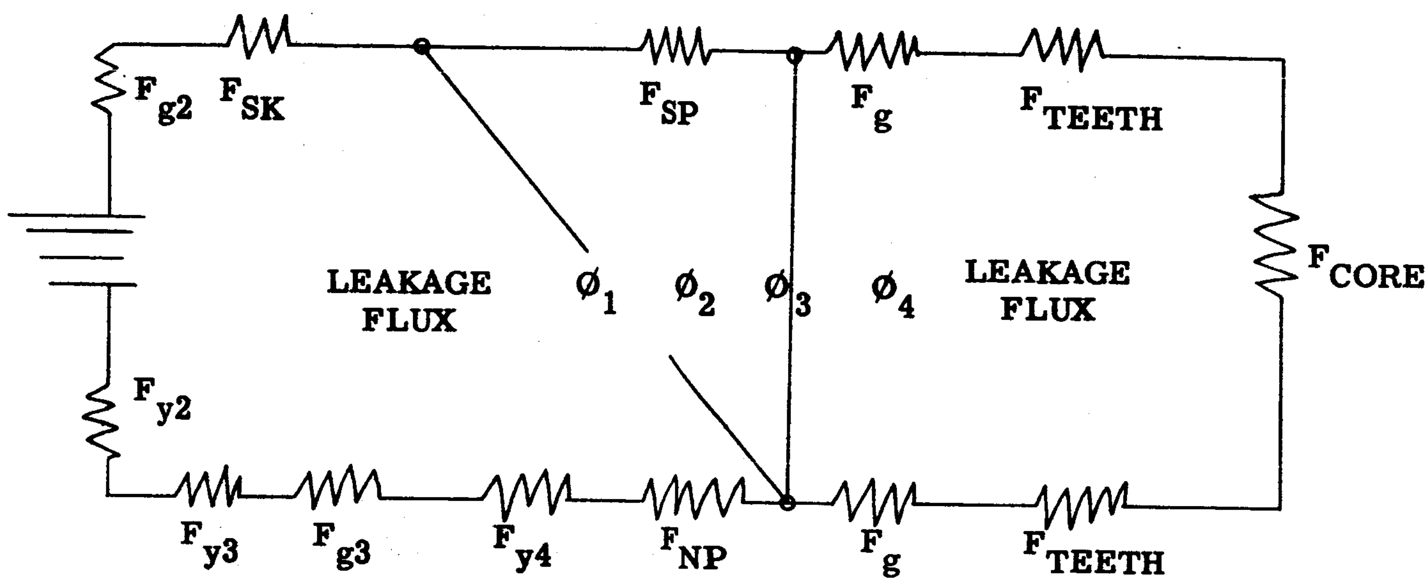
$$\ell_4 = \left(\frac{d_r}{2} - t_{SP}\right) \sin \frac{2\pi}{P}\left[1 - \frac{\alpha}{4}\right] - \frac{b_{NP}}{2}$$

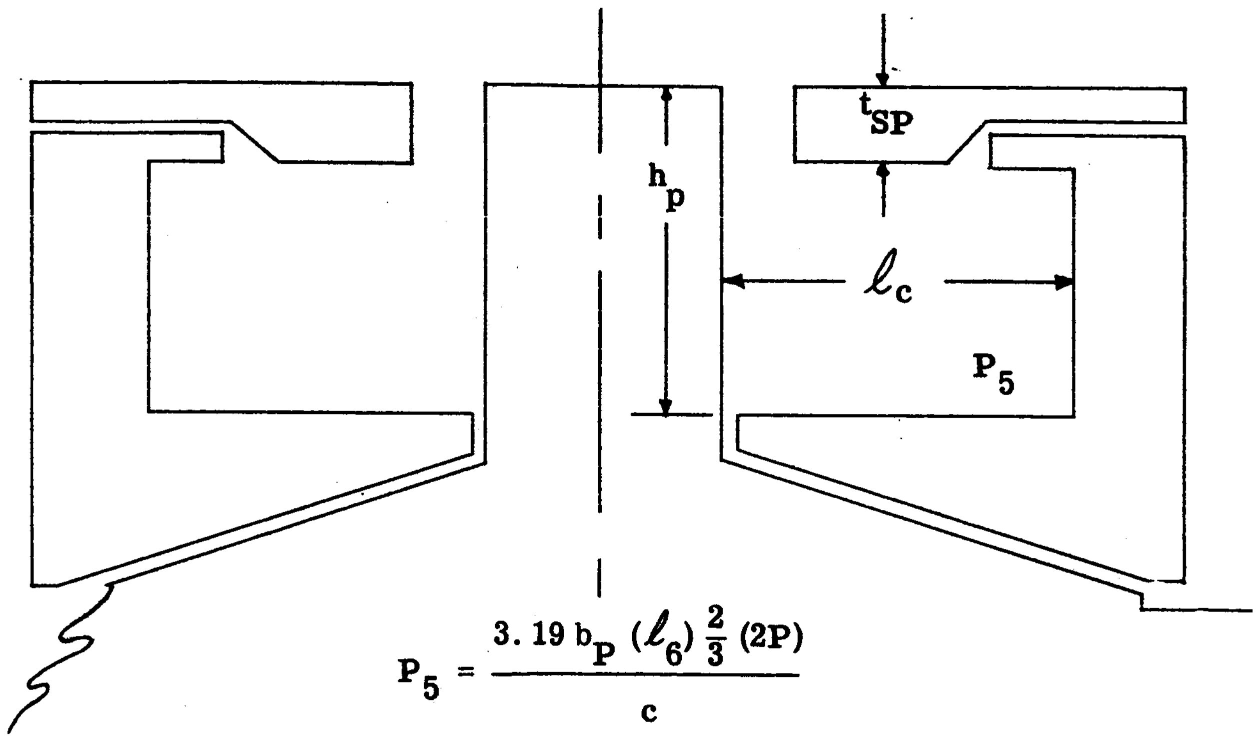


FOUR (4) POLE ALTERNATOR

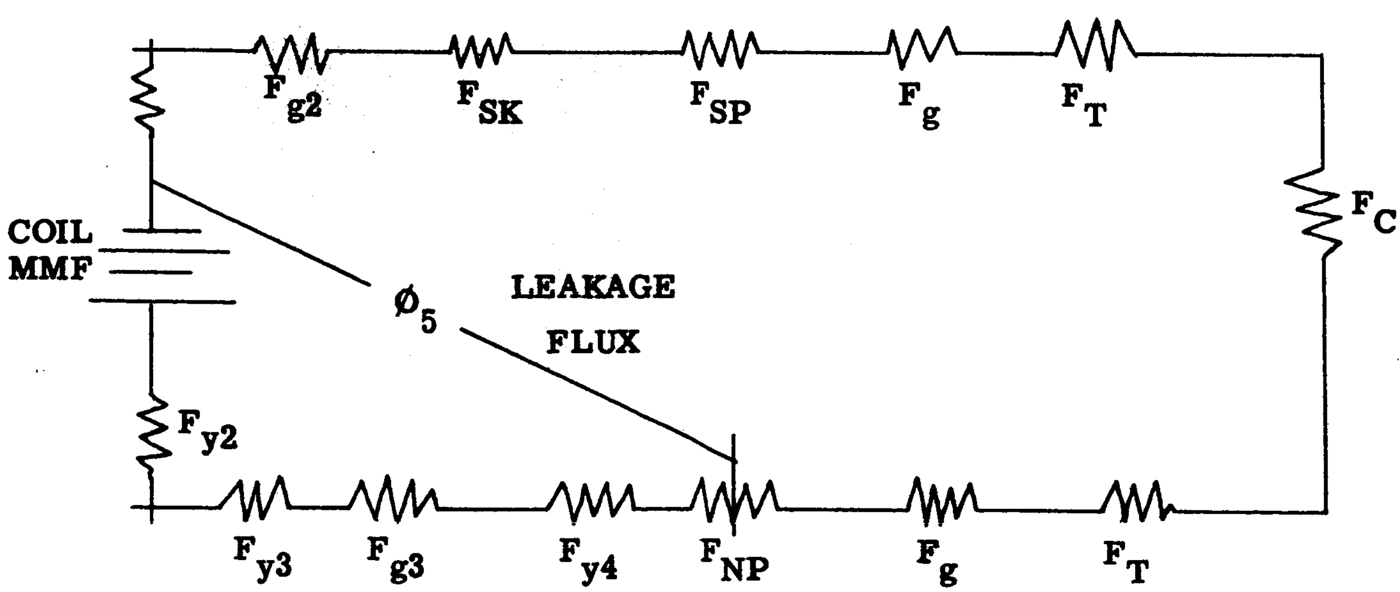


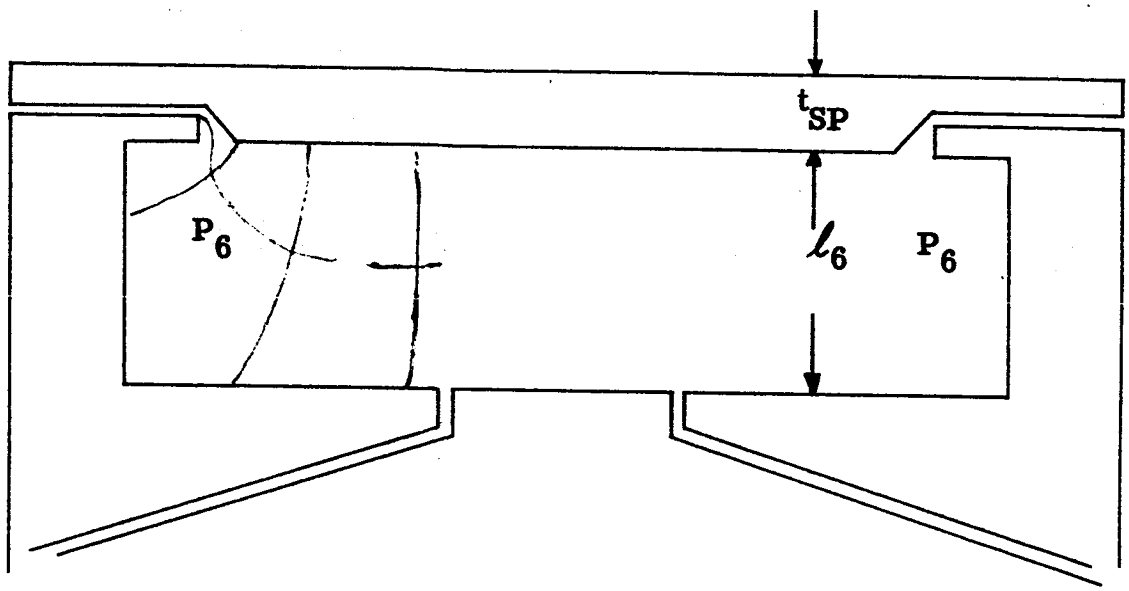
EIGHT (8) POLE ALTERNATOR


F g2
F SK
F SP
F g
F TEETH
LEAKAGE FLUX
Ø1
Ø2
Ø3
Ø4
LEAKAGE FLUX
F CORE
F y2
F y3
F g3
F y4
F NP
F g
F TEETH

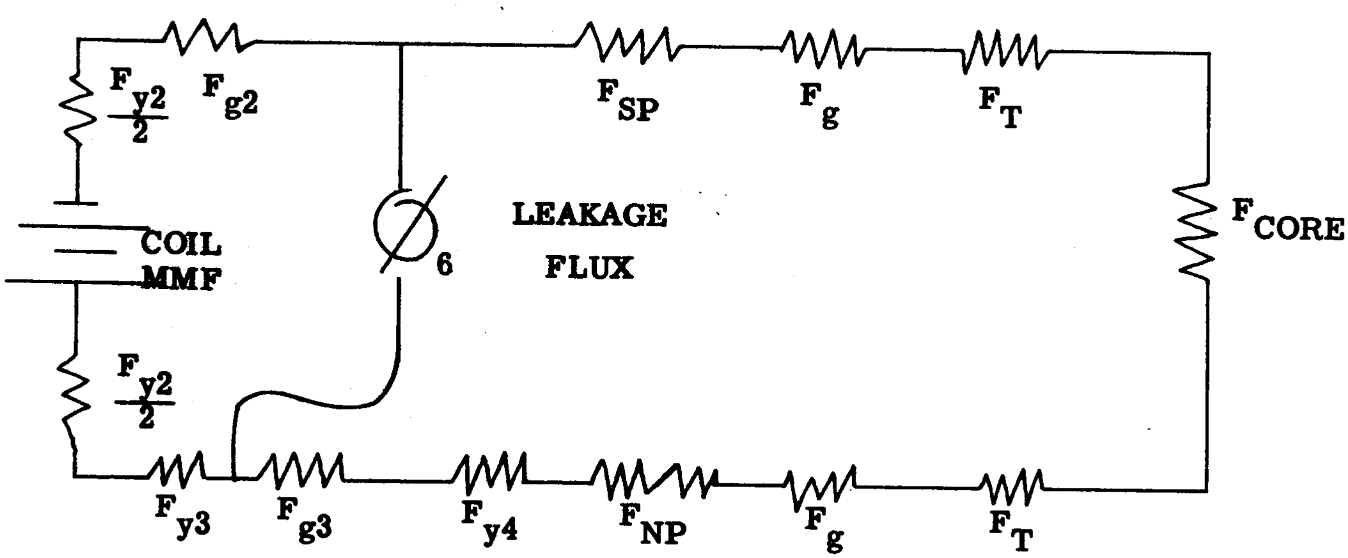


$$P_5 = \frac{3.19\, b_P\, (\ell_6)\, \frac{2}{3}\, (2P)}{c}$$





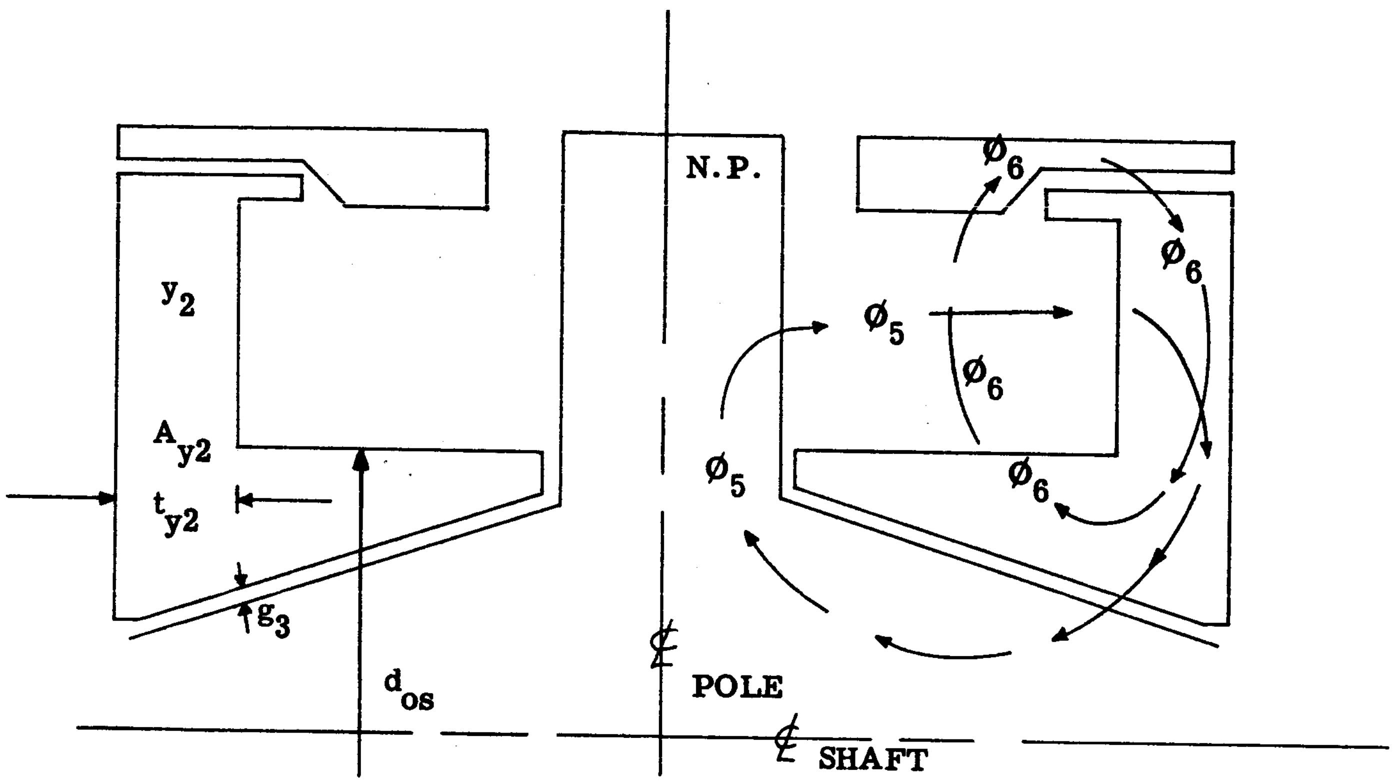
FLUX LEAKAGE ACROSS FIELD COILS



$$P_6 = \frac{3.19\,\ell_c\,\alpha\,(d_r - 2t_{SP})\,\frac{\pi}{P}\,(P)}{\ell_6}$$

$$= \frac{3.19\,\ell_c\,\alpha\,(d_r - 2t_{SP})\,\pi}{\ell_6}$$

Leakage Fluxes ϕ_5 and ϕ_6
(Leakage across the field coil ϕ_6,
and through the field coil ϕ_5)



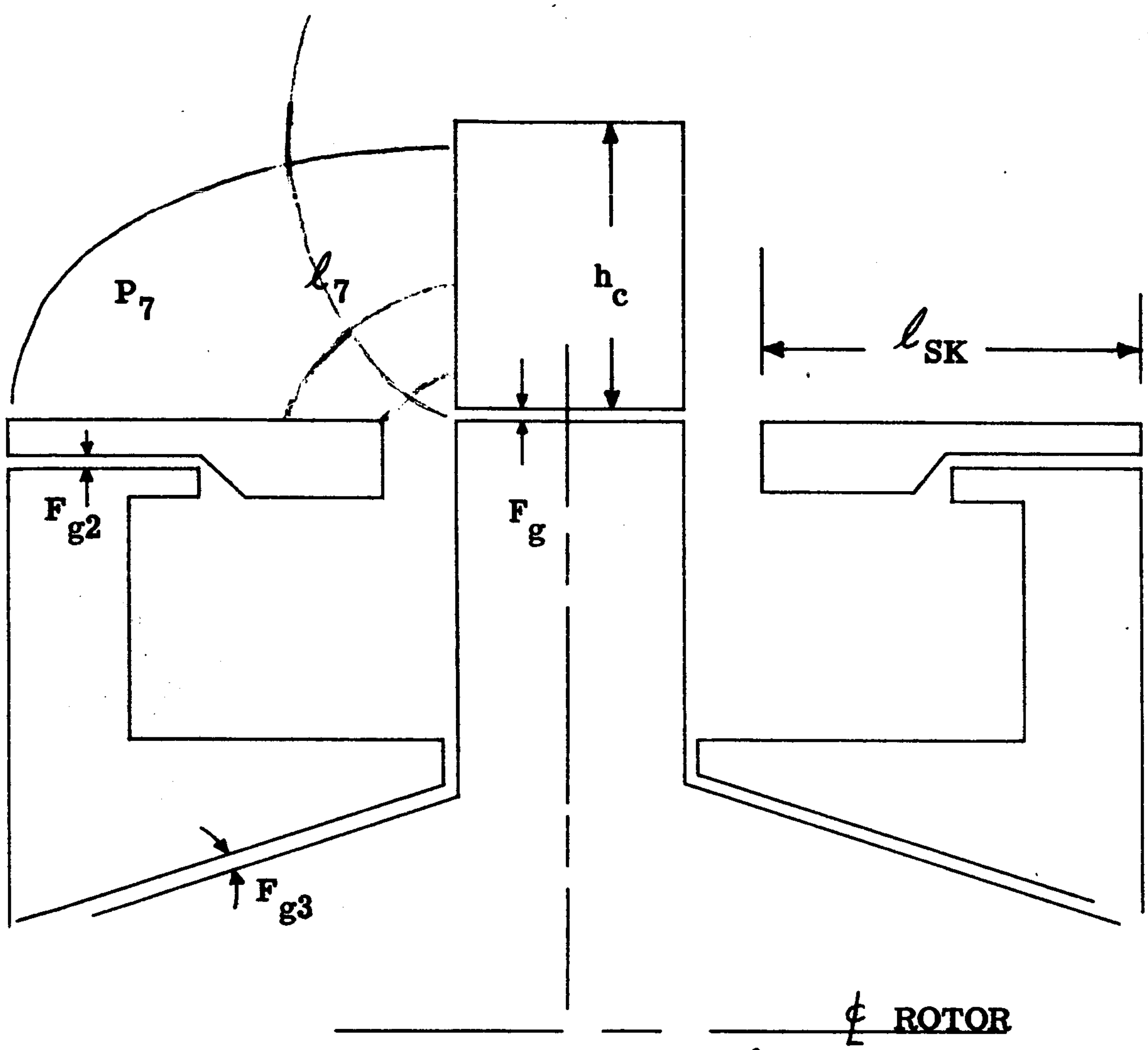
d_{os} = diameter of outer shaft

A_{y2} = area of yoke at smallest section

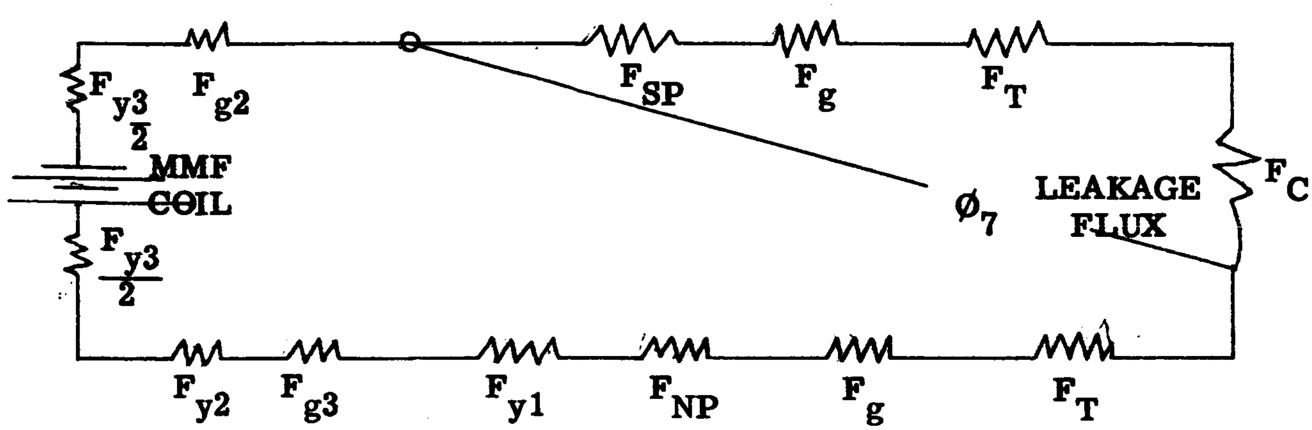
$A_{y2} = d_{os}\, t_{y2}$

The leakage flux ϕ_5 and ϕ_6 add to the flux in the yoke member y_2 but of the two leakage fluxes, only ϕ_5 adds to the flux crossing air gap g_3.

LEAKAGE FLUX FROM STATOR BACK-IRON TO ROTOR SKIRT - PATH 7



$$P_7 = \frac{3.19\,(d_r + h_c)\,(h_c + \ell_{SK})}{2h_c}$$



NO LOAD SATURATION

$1.05\, \phi_T$ = Estimated total flux including flux leakage from stator to rotor skirt - path 7.

$\frac{1.05\, \phi_T}{A_g}$ = Estimated air gap density at no load.

$\frac{1.05\, \phi_T}{A_T}$ = Estimated tooth density at no load.

$\frac{1.05\, \phi_P}{2A_C}$ = Estimated core density

MMF drop through main air-gap = F_g

$$F_g = \frac{B_g \text{ from above est.}}{3.19} (\ell_g)$$

MMF drop through teeth at tooth density est. above = F_T

MMF drop through core at core density est. above

Total MMF drop across flux leakage path from stator core to rotor skirt (Path 7) = $F_g + F_T + F_C$.

The drop across the south pole is negligible at no load and not likely to be large at any load. For this reason it is ignored.

Leakage flux through leakage path seven. Leakage from stator back-iron to rotor skirt = ϕ_7

$$\phi_7 = MMF_7 (P_7) = (F_g + F_T + F_C)\, P_7$$

Compare ϕ_7 with estimated value

Estimated $\phi_7 = \phi_P\,(.05)\,P$

If $\dfrac{\phi_7 - \phi_P\,(.05)\,P}{\phi_7} = \pm\,.10$ or less, proceed. If greater than .10

repeat calculations using

$$\frac{\phi_7 + P\phi_P}{P\phi_P}\,\frac{(\phi_T)}{A_g} = B_g$$

$$\frac{(\phi_7 + P\phi_P)}{P\phi_P}\,\frac{\phi_T}{A_T} = B_T$$

Obtain new ϕ_7

Calculate leakage fluxes 1, 2, 3, 4

Pole to pole leakage fluxes are

$$\phi_1,\ \phi_2,\ \phi_3,\ \phi_4$$

$$\phi_{1,2,3,4} = (2F_g + 2F_T + F_C)\,(P_1 + P_2 + P_3 + P_4)$$

$$B_{NP} = \frac{\phi_P + \dfrac{\phi_{1\text{-}4} + \phi_7}{P}}{A_{NP}} = \text{north-pole flux density}$$

$$B_{SP} = \frac{\phi_P + \dfrac{\phi_{1\text{-}4} + \phi_7}{P}}{2A_{SP}} = \text{south-pole (tube) flux density}$$

F_{NP} = MMF drop corresponding to B_{NP}

F_{SP} = MMF drop corresponding to B_{SP}

Flux density in auxiliary air-gap = B_{g2}

$$B_{g2} = \frac{\phi_P + P + \phi_{1-4} + \phi_7}{2A_{g2}}$$

MMF drop across auxiliary air-gap = F_{g2}

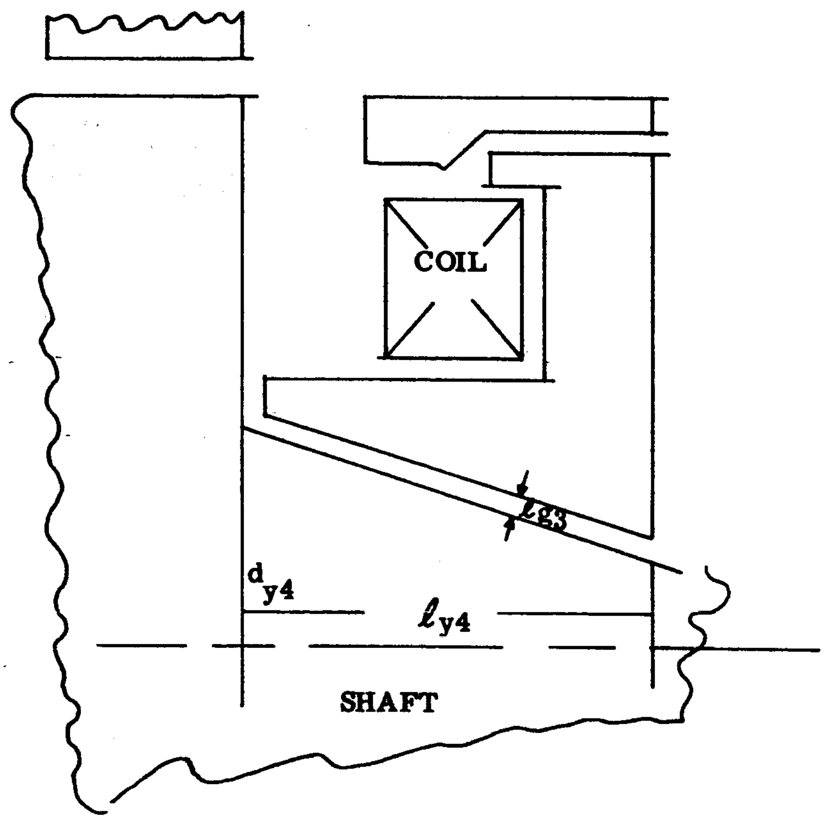
$$F_{g2} = \frac{B_{g2}}{3.19}$$

$$A_{y4} = \frac{d_{y4}^{\,2}}{4} = \text{Area Shaft (in}^2\text{)}$$

Flux density in shaft = B_{y4}

$$B_{y4} = \frac{\phi_P + P + \phi_{1-4} + \phi_7}{A_{y4}}$$

$MMF_{y4} = F_{y4} = H\ell_{y4}$ where H is the AT/in. at B_{y4} for shaft steel.



Flux density in 2nd auxiliary air gap = B_{g3}

$$B_{g3} = \frac{\phi_P \times P + \phi_{1-4} + \phi_7}{2A_{g3}}$$

MMF drop across 2nd auxiliary air-gap = F_{g3}

$$F_{g3} = \frac{B_{g3}}{3.19} \ell_{g3}$$

Leakage flux from north pole (spider pole) through the field coil = ϕ_5

$$\phi_5 \text{ (first calculation} = \left[F_{g2} + F_{SP} + (2F_g) + 2F_T + F_C + F_{NP}\right] P_5$$

Calculate new MMF drop in NP

$$B_{NP} = \frac{\phi_P + \dfrac{\phi_{1-4} + \phi_7 + \phi_5}{P}}{A_{NP}}$$

$$MMF_{NP} = (H_{at}\, B_{NP})\, H_P$$

$$\text{New } B_{g3} = \frac{\phi_P \times P + \phi_{1-4} + \phi_7 + \phi_5}{A_{g3}}$$

$$\text{New } F_{g3} = \frac{B_{g3}}{3.19} \ell_{g3}$$

Leakage flux across field coils from inner yoke to south-pole tube = ϕ_6

$$\phi_6 = \left[F_{SP} + 2F_g + 2F_T + F_C + F_{NP} + F_{g1} + F_{g3}\right] P_6$$

Add ϕ_6 to flux in yoke and tube.

Calculate flux density in the tube at the inboard edge of the auxiliary air gap g_2 to be sure that the tube is not saturating at that point.

$$\text{Final } B_{g2} = \frac{(\phi_P \times P) + \phi_{1-4} + \phi_7 + \phi_6}{A_{g2}}$$

$$\text{Final } F_{g2} = \frac{\text{Final } B_{g2} \, \ell_{g2}}{3.19}$$

$$F_{y2} = \frac{\phi_P \times P + \phi_{1-4} + \phi_7 + \phi_6 + \phi_5}{2A_{y2}}$$

$A_{y2} = \pi d_{os} \, t_{y2}$ = Smallest section of the yoke as shown in figure

Total ampere turns drop at no load is

$$F_{NL} = 2F_g + F_T + F_C + F_{NP} + F_{SP} + F_{g2} + F_{y2} + F_{y3} + F_{g3} + F_{y4}$$

REACTANCES AND TIME CONSTANTS

X_{ad} = The fictitious reactance due to armature reaction in the direct axis.

$$X_{ad} = \frac{.9\, n_e\, I_{ph}\, \ell_m\, t_d}{P\,(2F_g + F_{g2} + F_{g3})} \times 100$$

X_{aq} = The fictitious reactance due to armature reaction in the quadrature axis.

$$X_{aq} = \frac{C_q\, X_{ad}}{C_{m\,1}} \times 100$$

SYNCHRONOUS REACTANCE--(X_d and X_q) The steady state short circuit reactance. In the direct axis

$$X_d = X_\ell + X_{ad}$$

and in the quadrature axis

$$X_q = X_\ell + X_{aq}$$

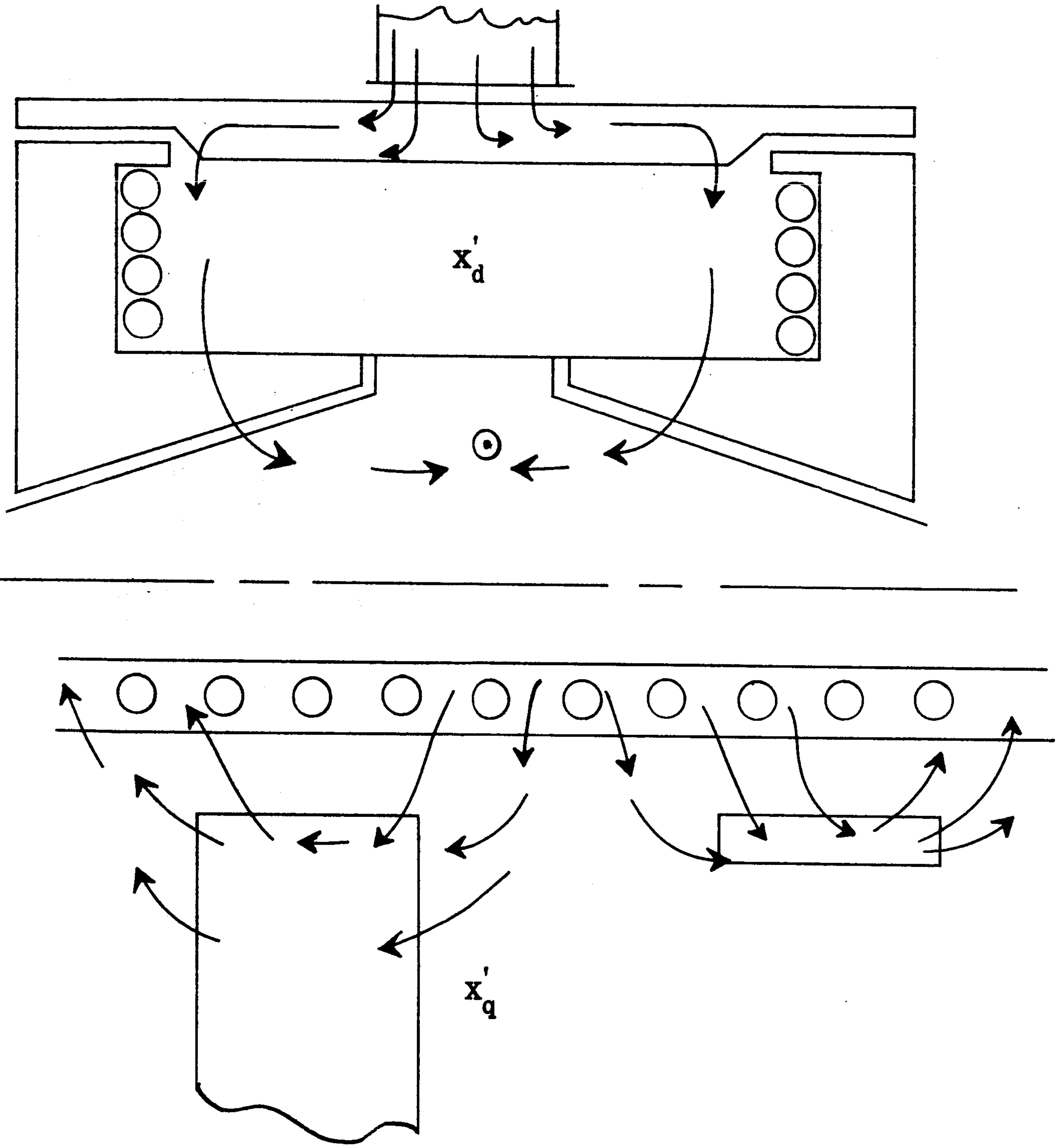
When current is suddenly applied to a generator stator (a step load) there is no flux linkage with the field winding during the first instant, and during that first instant all flux due to the armature mmf is forced through the field coil leakage paths.

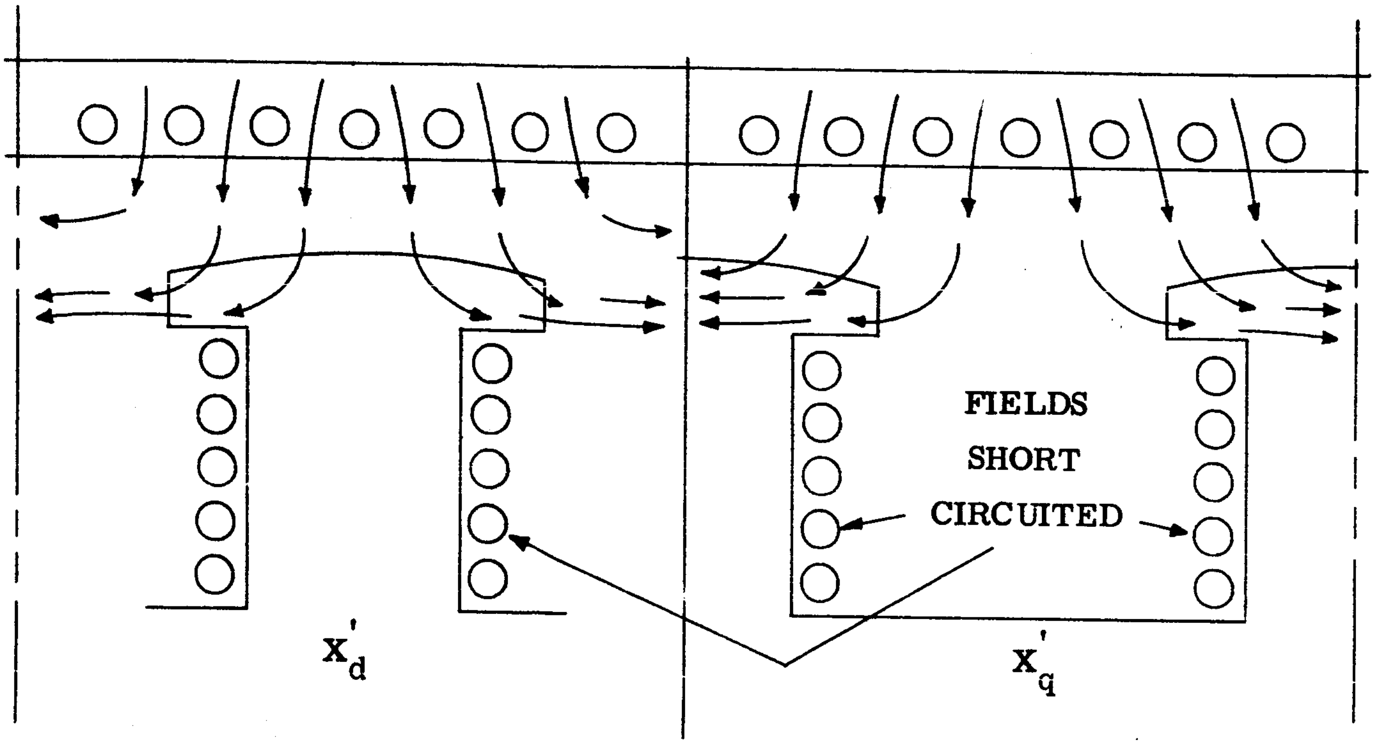
The inductance of the field coil leakage paths in the direct axis is L_d' and the reactance is

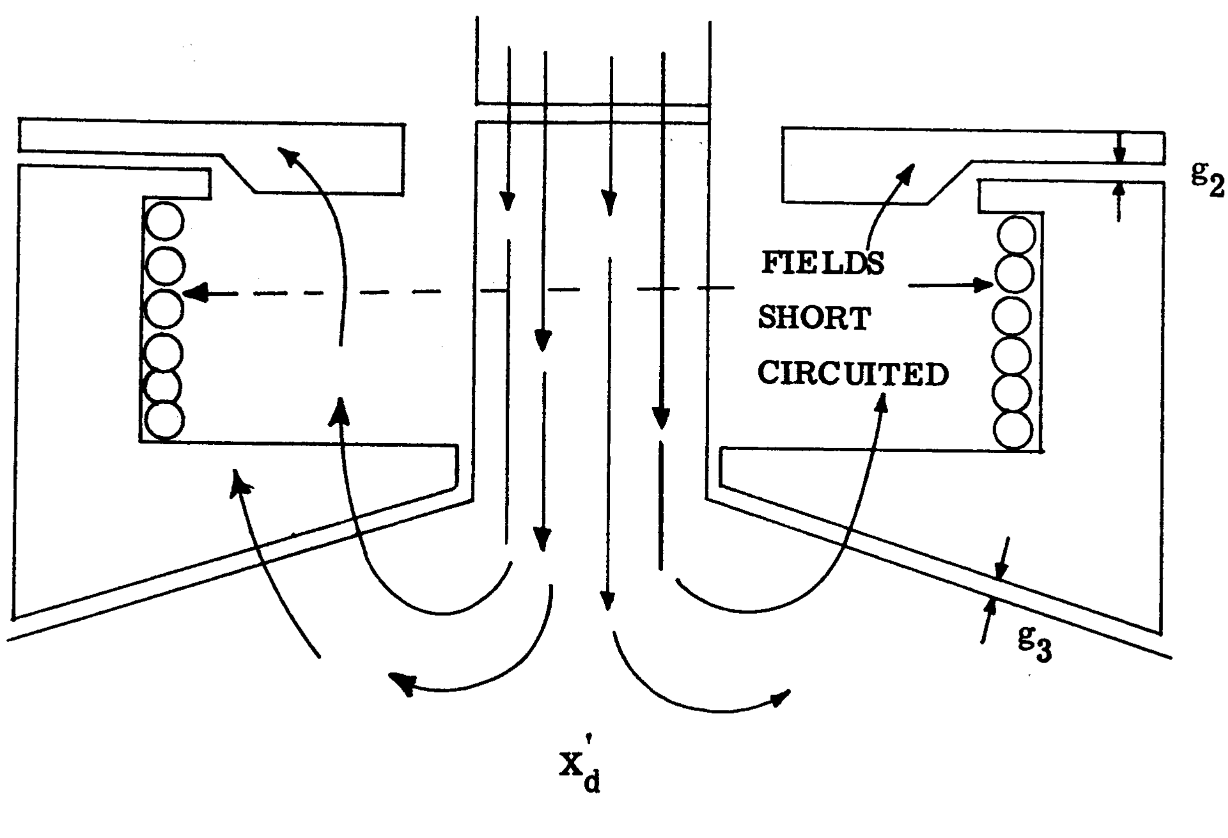
$$X_d' = 2\pi f\, L_d'$$

Since X_d' includes stator leakage reactance, X_d' can be written as

$$X_{du}' = X_F' + X_\ell = \text{The unsaturated transient reactance.}$$


x_d'
x_q'


FIELDS
SHORT
CIRCUITED
X_d'
X_q'


FIELDS
SHORT
CIRCUITED
g_2
g_3
X_d'

X_d' is usually considered to be about 88% to 90% of X_{du}' and the lower value is called the saturated transient reactance. It is the value found by testing at rated voltage.

THE EFFECTIVE FIELD LEAKAGE REACTANCE (X_F'). The reactance which added to the stator leakage reactance gives the transient reactance X_{du}'.

When unit fundamental armature ampere turns are suddenly applied on the direct axis, an initial field current (I_f) will be induced. The value of this initial field current will be just enough to make the net flux interlinking the field because of the field current and the armature current zero. The field ampere turns will equal the armature ampere turns.

$$X_F' = X \frac{P}{\ell}\left[\frac{\left(\frac{C_1}{C_P}\right)^2 {P_g}^2}{2\pi P_e \left(\frac{g_e'}{g_e}\right)^2}\right] \%$$

$$X_{du}' = X_F' + X_\ell$$

$$g_e' = g_e\left(\frac{2F_g + F_{g2} + F_{g3}}{2F_g}\right)$$

where F_g, F_{g2}, F_{g3} are calculated at rated load.

F_g = Ampere turns drop across single main air gap (g_e)

F_{g2} = Ampere turns drop across the outer auxiliary gap (g_2)

F_{g3} = Ampere turns drop across the inner auxiliary gap (g_3)

$$P_e = \frac{\phi_{g2} \text{ @ NL}}{I_f N_c \text{ @ NL}}$$

UNSATURATED TRANSIENT REACTANCE -- (X'_{du}) The transient reactance due to the field winding assuming unsaturated conditions.

$$X'_{du} = X_{\ell} + X_F$$

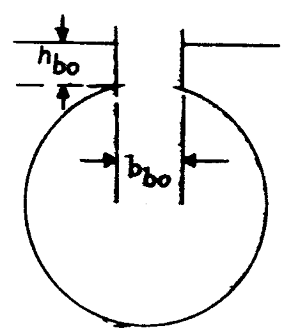
SATURATED TRANSIENT REACTANCE -- (X'_d) The transient reactance due to the field winding assuming normally saturated conditions.

$$X'_d = .88\, X'_{du}$$

NUMBER OF DAMPER BARS -- (n_b) The number of damper bars per pole.

BAR SIZE -- The size of the damper bars.

BAR PITCH -- (t_b) The damper bar pitch. This is the distance between the centerlines of adjacent damper bars. Also indicate the height of the slot opening above the damper bar (h_{bo}) and the width of this opening (b_{bo}).

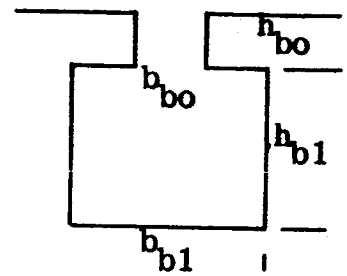


DAMPER LEAKAGE REACTANCE -- (X_{Dd} and X_{Dq}) The leakage reactance of the damper winding. In the direct axis the dimensions corresponding to the end bar next to the pole tip are used.

For rectangular square damper bars

$$\lambda_b = 6.38\left(\frac{h_{bo}}{b_{bo}} + \frac{h_{b1}}{3b_{b1}} + .5\right)$$

$$\lambda_{pt} = 6.38\left[\frac{b_n - t_b\,(n_b - 1)}{3g_e}\right]$$



$$\lambda_{Dd}\left[\cos\left\{\frac{(n_b - 1)\,t_b\pi}{2t_p}\right\}\right]\frac{(\lambda_b + \lambda_{pt})\,\lambda_F}{\lambda_b + \lambda_{bt} + \lambda_F}$$

$$X_{Dd} = X\lambda_{Dd}$$

In the quadrature axis the dimensions corresponding to the bar in the center of the pole is used.

For rectangular square bars

$$\lambda_{Dq} = \frac{20t_b}{t_r}\left[\frac{h_{bo}}{b_{bo}} + \frac{h_{b1}}{3b_{b1}} + .5 + \frac{g}{t_b}\right]$$

$$X_{Dq} = X\lambda_{Dq}$$

For round damper bars use the constant 0.62 in place of $h_{b1}/3b_{b1}$ in the above formulas.

SUBTRANSIENT REACTANCE -- (X_d'' and X_q'') The subtransient reactance due to the damper winding. In the direct axis

$$X_d'' = X_\ell + X_{Dd}$$

and in the quadrature axis

$$X_q'' = X_\ell + X_{Dq}$$

~~If the machine does not have a damper winding~~

$$X_d'' = X_d'$$

$$X_q'' = X_q'$$

NEGATIVE SEQUENCE REACTANCE -- (X_2) The reactance presented to negative sequence currents in the stator of the generator.

When negative sequence currents are applied to the stator winding they produce a backward rotating mmf traveling at synchronous speed with respect to the stator and at twice synchronous speed with respect to the rotor.

Currents of twice rated frequency are induced in the pole head winding or in the solid pole head, keeping the flux linkages of the pole circuits at almost zero value. The flux due to the armature current is forced into the damper or pole head winding leakage paths. These paths are the same as for the subtransient reactances.

L_2 = Armature flux linkages per ampere when negative sequence currents are flowing. This includes the stator leakage inductance also.

$$X_2 = \frac{X_d'' + X_q''}{2}$$

or the average between the quadrature and direct axis subtransient reactances. It is approximately equal to X_d'' or to $X_{Dd}'' + X_\ell$

where

X_{Dd}'' = Direct axis damper leakage

NEGATIVE SEQUENCE REACTANCE -- (X_2) The reactance presented to the flux field which rotates at synchronous speed in a direction opposite to that of the rotor.

$$X_2 = \frac{X_m\left[4\xi + 4\xi^2 + n^2\right]}{n^2 + 4\,(1+\xi)^2} + X_\ell$$

where $\xi = \dfrac{X_D}{X_m}$

$$X_m = \frac{X_{ad}}{C_1 C_m}\left(\frac{2F_g + F_{g2} + F_{g3}}{F_{NL}}\right)$$

$$X_D = X\left[\frac{20}{n_b}\left(.62 + \frac{h_{bo}}{b_{bo}}\right)\right] + \frac{5X_m}{6n_b^{\,2}} \quad \text{For round slots}$$

$$X_D = X\left[\frac{20}{n_b}\left(\frac{h_{b1}}{3b_{b1}} + \frac{h_{bo}}{b_{bo}}\right)\right] + \frac{5X_m}{6n_b^{\,2}} \quad \text{For rectangular slots}$$

$$n = \frac{R_D}{X_m}$$

R_D = Damper resistance

APPROXIMATE CALCULATION OF NEGATIVE SEQUENCE IMPEDANCE

$R_2 + j\,X_2 = \mathcal{T}_2$ = Negative sequence impedance - %

$$R_2 = \frac{2R_D}{n^2 + 4\,(1+\xi)^2} + R_s$$

$$X_2 = \frac{X_m\left[4\xi + 4\xi^2 + n^2\right]}{n^2 + 4\,(1+\xi)^2} + X_\ell$$

R_D = damper resistance

$$R_D = \frac{100\,X_p\,(9 \times 10^6)}{f\,\ell}\left[\frac{\ell_b}{n_b\,a_b\,P} + \frac{.637\,d_{dr}}{a_{dr}\,P^2}\right]\%$$

P = poles

ρ = resistivity of bar and end ring materials ($.692 \times 10^{-6}$ for copper at 77 F)

f = frequency

ℓ = stack length

ℓ_b = active bar length

a_b = bar cross section (in.^{2})

d_{dr} = mean diameter of damper end ring

a_{dr} = cross section of damper end ring

$n = R_D/X_m$

$$X_m = \frac{X_{ad}}{C_1 C_m}\left(\frac{2F_g + F_{g2} + F_{g3}}{F_{NL}}\right)$$

$\xi = X_D/X_m$

$$X_D = X\left[\frac{20}{n_b}\left(.62 + \frac{h_{bo}}{b_{bo}}\right)\right] + \frac{5X_m}{6{n_b}^2} \quad \text{For round slots}$$

$$X_D = X\left[\frac{20}{n_b}\left(\frac{h_{b1}}{3b_{b1}} + \frac{h_{bo}}{b_{bo}}\right)\right] + \frac{5X_m}{6{n_b}^2} \quad \text{For rectangular slots}$$

R_s = stator winding resistance - %

X_ℓ = stator leakage reactance - %

ZERO SEQUENCE REACTANCE -- (X_o) The reactance drop across any one phase (star connected) for unit current in each of the phases. The machine must be star connected for otherwise no zero sequence current can flow and the term then has no significance.

$$X_o = X\left[\frac{K_{Xo}}{K_X}(\lambda_i + \lambda_{Bo}) + \frac{20(h_1 + 2h_3)}{12mqK_p^2K_d^2b_s} + .2\,\lambda_E\right]$$

$$\lambda_{Bo} = \frac{K_{Xo}}{K_X}\lambda_{Dq}$$

$$\lambda_{BWO} = \frac{K_{Xo}}{K_p^2}(.07\,\lambda_a)$$

for machines with damper windings

$$\lambda_{Bo} = \frac{\lambda'_{Bo} + \lambda_{BWo}}{(\lambda'_{Bo})(\lambda_{BWo})}$$

and for machines without damper windings

$$\lambda_{Bo} = \lambda_{BWo}$$

and

$$K_{Xo} = \frac{3y}{mq} - 2$$

$$K_X = \left(\frac{3y}{4mq} + \frac{1}{4}\right) \text{ for pitches of 66-2/3\% to 100\%}$$

$$K_X = \left(\frac{3y}{2mq} - \frac{1}{4}\right) \text{ for pitches of 33-1/3\% to 66-2/3\%}$$

for a one conductor per slot winding

$$K_{Xo} = K_X = 1$$

OPEN CIRCUIT TIME CONSTANT -- (T'_{do}) The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit.

$$T'_{do} = \frac{L_F}{R_F} \text{ second}$$

TRANSIENT TIME CONSTANT -- (T'_d) The time constant of the transient reactance component of the alternating wave.

$$T'_d = \frac{X'_d}{X_d} T'_{do}$$

ARMATURE TIME CONSTANT -- (T_a) The time constant of the DC component.

$$T_a = \frac{X_2}{(2)(100 \ \ fr_a)} \text{ seconds}$$

$$r_a = \frac{\text{Stator } I^2 R \text{ (KW)}}{\text{Rated KVA}}$$

SUBTRANSIENT TIME CONSTANT -- (T''_d) The time constant of the subtransient component of the alternating wave. This value has been determined empirically from tests on large machines and

$$T''_d = .035 \text{ second at 60 cycles.}$$

$$T''_d = .005 \text{ second at 400 cycles.}$$

LOAD SATURATION - FULL LOAD

$$E_{NL} = E_{ph} + IR$$

$$\psi = \text{Tan}^{-1}\left[\frac{\text{Sin}\ \theta + X_q}{\text{Cos}\ \theta}\right]$$

= Angle between output current and ℓ_d (see figure

θ = Power factor angle = $\text{Cos}^{-1}\left[\text{P.F.}\right]$

$\epsilon = \psi - \theta$ = angle between terminal volts and ℓ_d (see figure

$$e_d = \text{Cos}\ \epsilon + X_d\ \text{Sin}\ \psi$$

= Voltage that would be generated at no load and no saturation - the air-gap voltage behind the synchronous reactance.

$$F_{gL1} = e_d\ F_{gNL}$$

= Air-gap ampere turns under load if there were no stator leakage flux from the core to the rotor skirt.

F_{gNL} = Air-gap ampere turns at no load without the stator leakage flux from the core to the rotor skirt.

$$F_{TL1} = F_{TNL}\ (1 + \text{P.F.})$$

= First approximation of the teeth ampere turn drop at full load.

F_{CL} = F_{CNL} approximately because the core to rotor leakage flux does not increase the core density. The stator tooth to tooth leakage flux approximately off-sets the theoretical increase in core flux under load.

$$\phi_{7-1} = P_7 \left[F_{gL1} + F_{TL1} + F_C \right]$$

= First approximation of the leakage flux from the stator back-iron to the rotor skirt.

$$F_{gL} = F_{gL1} + \frac{\phi_{7-1}}{3.19} g'$$

= Total air-gap ampere turns at full load.

$$\phi_{TL1} = \phi_{NL} + \frac{\phi_{7-1}}{C_P}$$

= Theoretical total flux at full load. First approximation

$$B_{TL} = \frac{\phi_{TL}}{A_T}$$

= Tooth density at full load above the north pole.

$$F_{TL} = \ell_T H_{BTL} (1 + P.F.)$$

H_{BTL} = Ampere turns drop/inch corresponding to a tooth density of B_{TL}

$$\phi_{7L} = P_7 \left[F_{gLT} + F_{TL} + F_C \right]$$

$$\phi_{TL} = \phi_{NL} + \frac{\phi_7}{C_P}$$

= Theoretical total flux at F. L. second approximation.

$$\phi_{1,2,3,4} = (P_1 + P_2 + P_3 + P_4)(2F_{gL} + 2F_{TL} + F_C)$$

= Leakage flux from pole to pole in the rotor.

$$\phi_{PL} = \phi_{PNL}\left[\ell_d - .0093\, X_{ad} \operatorname{Sin} \psi\right]$$

$$\phi_{PL} = 1.10\ \phi_{PNL} \text{ for Cos } \theta = >.90$$

$$\phi_{PNL} = \text{Flux/pole Calc at NL voltage} = V + 1R$$

$$\phi_{SP\text{-}FL} = \frac{\phi_{PL}}{2} + \frac{\phi_{1234}}{2P}$$

= Flux in south pole

A_{SP} = Area of south pole entry section. Section at edge of stator stack.

$$B_{SP\text{-}FL} = \frac{\phi_{SP\text{-}FL}}{A_{SP}}$$

= Flux density in S.P. at full load

$$F_{SP\text{-}FL} = H_{SP\text{-}FL}\, \ell_P$$

= Ampere turns drop through S.P. at FL

$$\phi_{NP\text{-}FL} = \phi_{PL} + \frac{\phi_7}{P} + \frac{\phi_{1234}}{P}$$

= Flux in north pole without leakage flux ϕ_5

A_{NP} = Area of north pole (in.^{2}) at base

$$B_{NP-FL-1} = \frac{\phi_{NP-FL}}{A_{NP}}$$

= First approximation of north pole flux density at full load

$$F_{NP-FL-1} = H_{NP-FL} \quad P$$

= Ampere turns drop in north pole - first approximation

P_6 = Leakage permeance across field coil from rotor shaft outer diameter to the inner surface of the rotor skirt

$$\phi_6 = P_6 \left[F_{SP-FL} + F_{NP-FL} + 2F_g + 2F_T + F_C \right]$$

= Leakage flow across field coil

$$A_{SK} = \pi (d_r - t_{SK}) \, t_{SK} \text{ in}^2$$

= Area of skirt at entry edge of auxiliary air-gap g_2

$$\phi_{SK-FL} = (\phi_{SP-FL}) \frac{P}{2} + \phi_7 + \frac{\phi_6}{2}$$

$$B_{SK-FL} = \frac{\phi_{SK-FL}}{A_{SK}}$$

= Flux density in the rotor skirt at full load

$$F_{SK-FL} = H_{SK-FL} \, \ell_{SK}$$

This should be an insignificant ampere turn drop. The calculation of B_{SK-FL} is in the program for a check on a possible bottle-neck

P_5 = Permeance of leakage flux path from north pole through the field coil to the yoke y_2

$$B_{g2\text{-}FL} = \frac{\phi_{SK\text{-}FL}}{A_{g2}} \qquad \left\{ \begin{array}{l} \text{Flux density in auxiliary air gap} \\ \text{at full load} \end{array} \right.$$

$$F_{g2\text{-}FL} = \frac{(B_{g2\text{-}FL})}{3.19} \ \ell_g$$

= Ampere turn drop across auxiliary air gap at full load

$$\phi_5 = P_5 \left[F_{NP\text{-}FL} + 2F_{g\text{-}FL} + 2\ F_{T\text{-}FL} + F_C + F_{SP\text{-}FL} + F_{g2\text{-}FL} \right]$$

= Leakage flux through field coil from north pole to yoke y_2

$$\phi_{y2\text{-}FL} = \phi_{SK\text{-}FL} + \frac{\phi_5}{2}$$

$$B_{y2\text{-}FL} = \frac{\phi_{y2\text{-}FL}}{A_{y2}}$$

Where A_{y2} is smallest cross-section (at base of yoke section)

$$F_{y2\text{-}FL} = \frac{H_{y2\text{-}FL}\ \ell_{y2}}{3}$$

= Ampere turn drop in the yoke section y_2. This MMF value should be insignificant and the calculation is here to call attention to a possible saturation point.

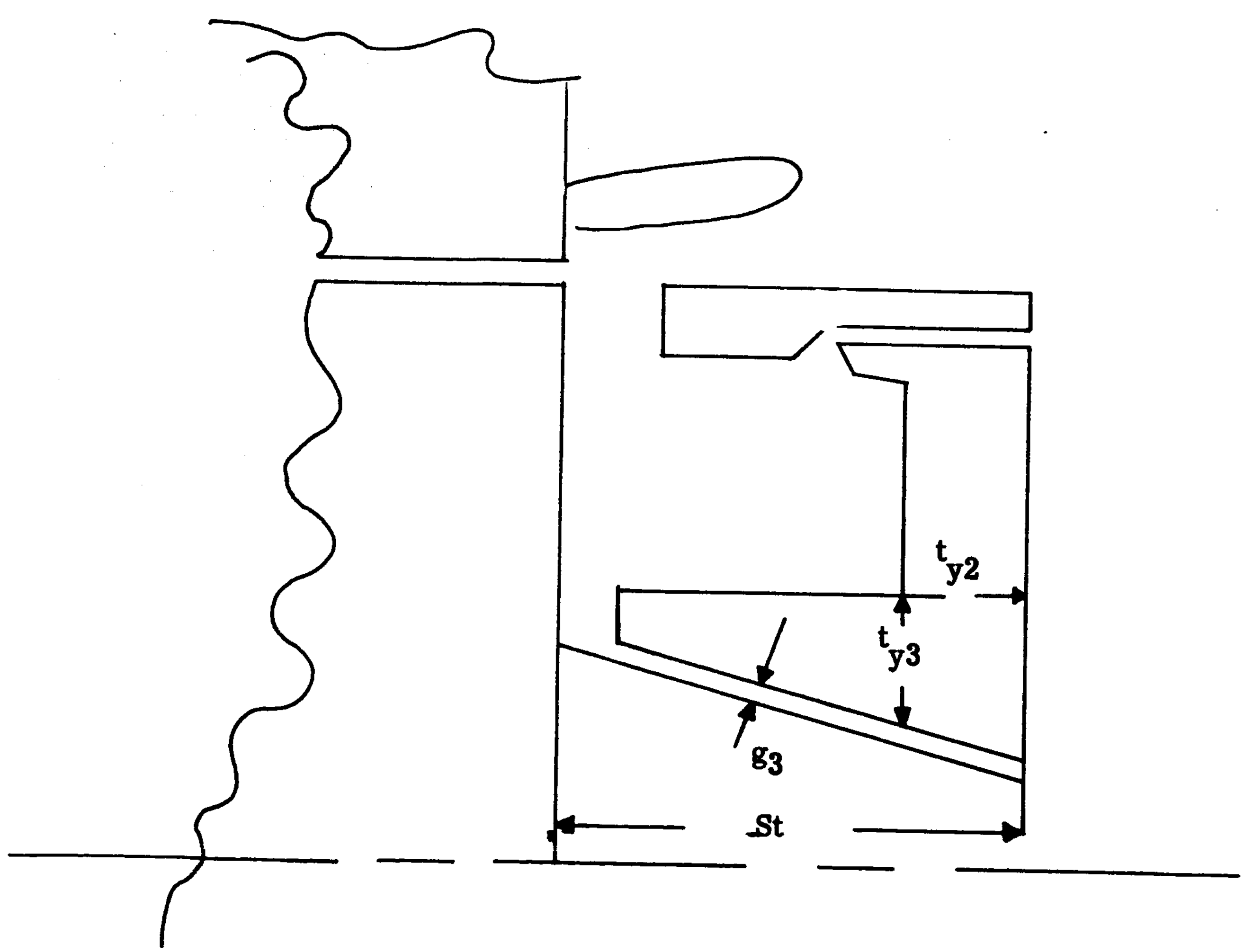
If the yoke section is made straight, of uniform thick-thickness, all of the ampere turn drop will be in the lower one-half of the yoke.

$$B_{y3\text{-}FL} = \frac{\phi_{y2\text{-}FL} \; \dfrac{S_t - t_{y2}}{S_t}}{A_y}$$

= Flux density in the stationary yoke section y_3 at the entry to the auxiliary air-gap g_3

$$F_{y3\text{-}FL} = H_{y3\text{-}FL}\,(S_t - t_{y2})$$

$H_{y3\text{-}FL}$ = Ampere turns drop/inch for material at flux density $B_{y3\text{-}FL}$



$$B_{g3-FL} = \frac{\phi_{y2-FL}}{A_{g2}}$$

$$F_{g3-FL} = \frac{B_{g3-FL}}{3.19} (g_3)$$

= Ampere turns drop across auxiliary air-gap g_3 at full load

$$B_{y4-FL} = \frac{(\phi_{y2-FL})}{A_{y4}}$$

= Flux density in shaft at entry to north poles

$$B_{NP-FL} = \frac{2\ (\phi_{y2-FL})}{A_{NP}}$$

= Flux density in north pole at base

$$F_{NP-FL} = \frac{H_{NP-FL}\ h_P}{2}$$

$$F_{FL} = \Big[2F_g + 2F_T + F_C + F_{SP} + F_{NP} + F_{SK} + F_{g2} + F_{y2} + F_{y3} + F_{g3} + F_{g4}\Big]$$

LOAD SATURATION AT .5, 1.5, 2.0 PER-UNIT LOAD

$$E_{NL} = E_{ph} + IR\ (\text{P.U. load})$$

$$\psi = \tan^{-1}\left[\frac{\sin\theta + X_q\ (\text{P.U. load})}{\cos\theta}\right]$$

$$\ell_d = \cos\epsilon + X_d\ (\text{P.U. load})\sin\psi$$

$$\frac{\phi_{PL}}{\phi_{PNL}} = \left[\ell_d - .93\,X_{ad}\ (\text{P.U. load})\sin\psi\right]$$

$$\frac{\phi_{PL}}{\phi_{PNL}} = 1.10 \text{ if } \cos\theta > .90$$

$\dfrac{\phi_{PL}}{\phi_{PNL}}$ is the increase in pole flux required because of distortion of the wave form and resultant decrease in C_1

ϕ_{PNL} is value calculated at NL voltage = V + IR

STATOR TOOTH LOSS -- (W_{TNL}, W_{TFL}, W_{TOL}) The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density.

$$W_{TNL} = .453\ (t_{s1/3} - b_s)\ Q\ell_s h_s K_Q \text{ watts}$$

$$K_Q = \left(\frac{B_t}{77.4}\right)^2 \times K$$

K = Watts/lb loss at 77.4 kl/in^2 density. Take from U.S.S. Steel Manual

The stator tooth loss under load (W_{TFL} & W_{TOL}) is increased because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings.

$$W_{TFL} = \left[2\,(.27X_d)^{1.8} + 1\right]\, W_{TNL}; \quad (X_d \text{ in per unit})$$

For W_{TOL} use X_d corresponding to the overload condition.

STATOR CORE LOSSES -- (W_C) The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density.

$$W_C = 1.42\,(D - h_c)\, h_c\, \ell_s K_Q$$

K_Q = Watts per pound loss from U.S.S. Electrical Steel Sheets Manual at a density of B_C.

POLE FACE LOSSES -- (W_{PNL}, W_{PFL}, W_{POL}) The pole surface losses are due to the slot ripple caused by the stator slots. They depend upon the width of the stator slot opening, the air gap, and the stator slot ripple frequency. The no load pole face loss (W_{PNL}) is calculated from Graph #2. K_1 = 7.0 for solid pole faces. Graph #2 is plotted on the basis of open slots and thus B_s on the curve equals b_o for partially closed ones. The pole face loss under load (W_{PFL}, W_{POL}) is calculated as

$$W_{PFL} = \left[\left(\frac{K_{sc}\, I_{ph}\, n_s}{c\, F_g}\right)^2 + 1\right] W_{PNL}$$

K_{sc} is obtained from Graph #3.

For W_{POL} use I_{ph} corresponding to the overload phase current.

DAMPER -- (W_{DNL}, W_{DFL}, W_{DOL}) The loss produced by the slot ripple in the damper winding. At no load this loss is calculated from curves #7 and #8. The damper loss under load (W_{DFL}, and W_{DOL}) for polyphase machines is calculated as

$$W_{DFL} = \left[\left(\frac{K_{sc}\, I_{ph}\, n_s}{c\, F_g}\right)^2 + 1\right] W_{DNL}$$

K_{sc} is obtained from Graph #3.

For W_{DOL} use I_{ph} corresponding to the overload phase current.

STATOR I^2R -- The copper loss based on the DC resistance of the winding. Calculate for the maximum expected operating temperature.

$$I^2R = m\, I_{ph}^2\, R_{ph}$$

EDDY -- The stator I^2R loss due to skin effect.

$$\text{Eddy Loss} = \left[\left(\frac{\text{Eddy Factor Top} + \text{Eddy Factor Bottom}}{2}\right) - 1\right] \text{Stator } I^2R$$

ROTOR I^2R -- The copper loss in the field winding.

$$I^2R = I_f^2\, R_f$$

SUM OF THE LOSSES -- The total losses at the various loads.

RATING -- The kilowatt rating of the generator.

RATING + LOSS -- The sum of the total losses and the KW rating.

PERCENT LOSS -- The total loss divided by the rating plus total loss.

PERCENT EFFICIENCY -- (100% - % loss).

STATOR WATTS/SQ. IN. -- The stator watts loss per sq. in. of stator periphery.

$$\text{Watts/in}^2 = \frac{\text{Stator (Tooth Loss + Core Loss} + I^2R + \text{Eddy Loss)}}{\pi D \ell}$$

ROTOR WATTS/SQ. IN. -- The rotor watts loss per sq. in. of rotor periphery.

$$\text{Watts/in}^2 = \frac{\text{Pole Face Loss + Damper Loss + Rotor } I^2R}{\pi d_r \ell_p}$$

POLE-FACE LOSSES IN SOLID POLE GENERATORS

IN BRIEF

Pole-face losses in solid rotor generators can limit the rotational speed, the output, or both. The following article discusses the calculation of, and the design limits imposed by the pole face losses.

GENERAL STATEMENT

Paradoxically, the solid rotor machine is proposed for high speeds and high air-gap flux densities when it cannot operate at speeds or loadings comparable to those of the laminated pole generators, without the penalty of high losses in the solid pole faces.

A solid-pole Lundell generator that operates over a speed range of two to one may require de-rating at the maximum speed because of pole-face losses. This de-rating is required because of the pole face losses under load - not the no load losses.

When the wide speed range generator operates at its maximum speed, the gap density is reduced and the reduction of losses due to the reduced flux density is greater than the loss increase due to the increase in tooth ripple frequency. The result at no load is a reduction in pole face losses. At full load though, the same stator current flows and the armature mmf is the same as it was at the lower speed.

Because of the doubled slot frequency, the pole face load losses at the top speed will be of the order of 3 times as great as at the 1/2 speed condition. The actual increase in pole face losses under load depends upon the slot opening, air gap length, ampere loading, and gap density.

SOURCE OF THE FORMULAE

T. Spooner and I. F. Kinnard "Surface Iron Losses with Reference to Laminated

Materials" Trans. AIEE, Vol. 43, 1924, pp 262-281.

The above reference points out that the following factors influence pole face losses:

1. Air gap induction Bg
2. Field form C.
3. Ratio of slot width to single air gap $\frac{b_s}{g}$
4. Tooth frequency f_t

*5. Tooth pitch τ_s or slot pitch

6. Resistivity of material (ρ)
7. Thickness of individual laminations t
8. Hysteresis Coefficient γ
9. Insulation between laminations
10. Effect of punching

* We use different symbol than Spooner and Kinnard

In the equation -

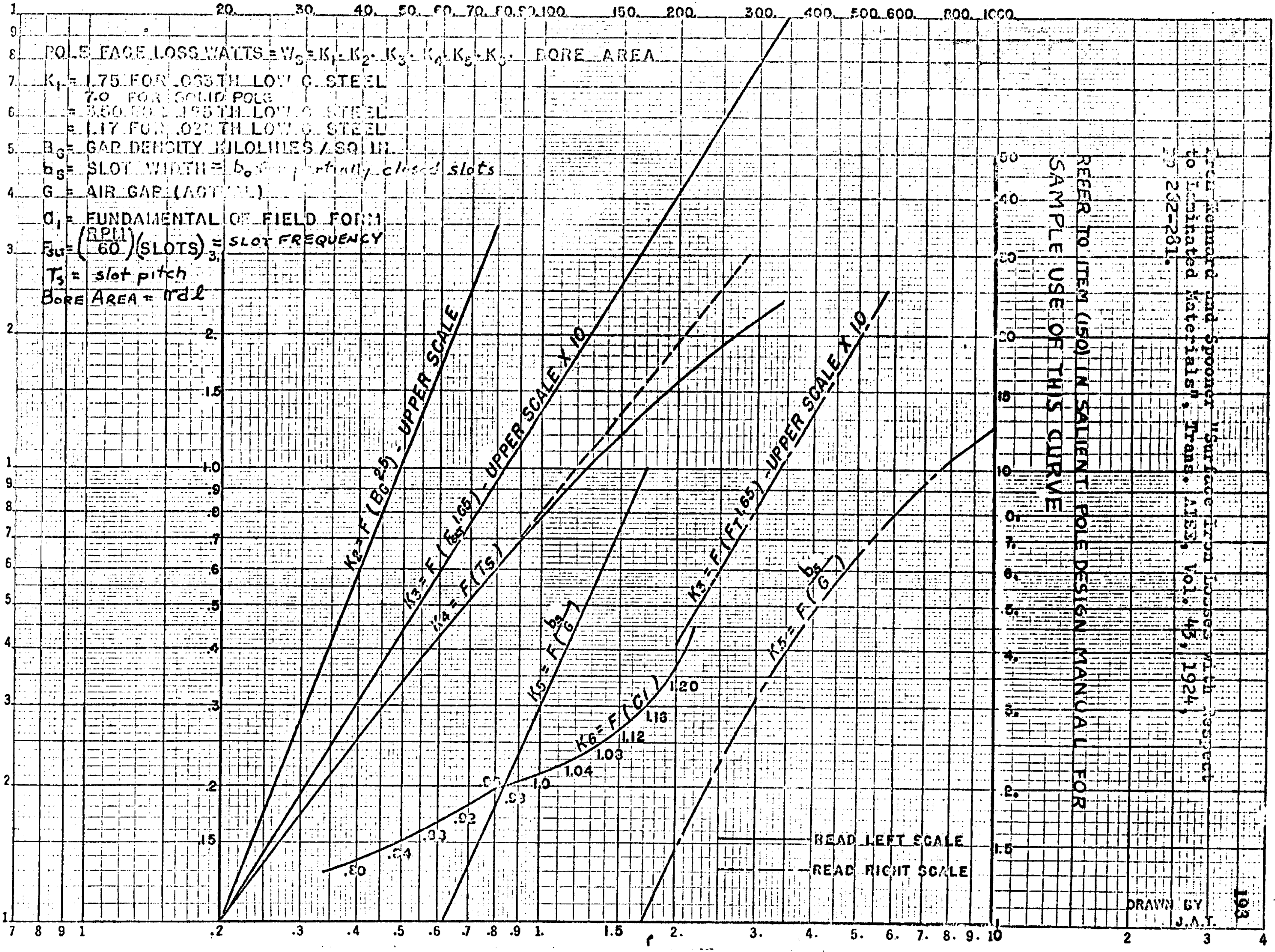
Pole face losses = $W_S = K_1 K_2 K_3 K_4 K_5 K_6$ (Bore area), the hysteresis coefficient is not used, the interlamination resistance is assumed high, no burrs are assumed to be shorting the laminations and the effect of work-hardening is assumed to be removed by annealing.

In the paper, Spooner and Kinnard summarize that as a rough approximation, surface losses vary as:

$$(Bg)^2, \ (f_t)^{1.5}, \ \frac{b_s}{g}^{1 \text{ to } 2} \quad (\tau_s)^1$$

In the text of the paper, higher exponents are used and the constant K_1 is adjusted to give the required accuracy. The exponents used in the curves given in the design manuals of this report are about 30% higher than the rough approximation given by Spooner and Kinnard, and account for interlaminated currents caused by imperfect insulation.

CURVE-2


POLE FACE LOSS WATTS = W_S = $K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot$ BORE AREA
K_1 = 1.75 FOR .035 TH LOW C. STEEL
7.0 FOR SOLID POLE
= 3.50 FOR .185 TH LOW C. STEEL
= 1.17 FOR .025 TH LOW C. STEEL
B_G = GAP DENSITY KILOLINES / SQ IN.
b_S = SLOT WIDTH = b_o for partially closed slots
G = AIR GAP (ACTUAL)
C_1 = FUNDAMENTAL OF FIELD FORM
$F_{SU} = \left(\frac{RPM}{60}\right)$ (SLOTS) = SLOT FREQUENCY
T_S = slot pitch
BORE AREA = $\pi d l$
$K_2 = F(B_G^{2.5})$ - UPPER SCALE
$K_3 = F(F_{SU}^{1.65})$ - UPPER SCALE X 10
$K_4 = F(T_S)$
$K_5 = F\left(\frac{b_S}{G}\right)$
$K_6 = F(C_1)$
$K_3 = F(F_T^{1.65})$ - UPPER SCALE X 10
$K_5 = F\left(\frac{b_S}{G}\right)$
1.20
1.18
1.12
1.03
1.04
1.0
.93
.95
.92
.83
.84
.80
READ LEFT SCALE
READ RIGHT SCALE
REFER TO ITEM (150) IN SALIENT POLE DESIGN MANUAL FOR SAMPLE USE OF THIS CURVE
From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924, pp 262-281.
DRAWN BY J.A.T.

SOLID-POLE P.F. LOSSES

For this study, tests were made on solid-pole generators using 4130 pole steel. Tests correlated within 5% of calculated losses when the constant $K_1 = 7.0$ was used. Load losses in the pole face are calculated just as for laminated poles.

Note: If the rotor is not relieved at the leading and trailing edges of the pole, the losses will be higher than those calculated with $K_1 = 7.0$. Such a condition might exist when 316 steel or Inconel X is welded between poles and the weldment is cylindrical. In such cases, the armature reaction flux causes high losses in the interpolar area. This discussion and calculation assumes that best conditions exist.

NO-LOAD POLE FACE LOSSES

The pole face losses are a function of the stator bore area, and when the stator tooth pitch is constant, the losses are a function of the rotor diameter. They are also functions of the gap density and under load they are functions of the stator loading. Since the RPM determines the tooth ripple frequency, the P.F. losses are a function of the RPM.

The flux density and speed of a specific, solid pole generator, are limited by the amount of heat that can be dissipated from the surface of the poles so without considering the output of the generator, the effect of slot pitch and air gap density on pole face losses can be observed, while the generator operates at no-load.

With a specified air gap density and specified slot pitch, the pole face losses can be made high enough to cause the machine to fail and this can happen without load being applied. It can happen to a laminated pole or to a solid pole generator.

The no load pole face losses in a solid pole generator are of the order of six (6) times as great, for the same stator design, as those in the pole faces of a laminated rotor. For this reason only the design limits for the solid pole generators are investigated here.

No load pole face losses are = fn $(Bg, \frac{b_s}{g}, f_T, \tau_s, C_1)$ where

Bg = air gap density, Kilolines/in^2

b_s = slot opening, inches

g = air gap length, inches

f_t = tooth ripple, cycles/sec

τ_s = tooth pitch on stator, inches

C_1 = fundamental of field form (a ratio)

For most of the following discussion, the following values are assumed fixed:

$$\frac{b_s}{g} = 2.0$$

$$\tau_s = .3''$$

$$C_1 = 1.0$$

Since $\tau_s = .3$, now the number of teeth is a function of d.

$$\text{No. Teeth} = \frac{\pi d}{.3}$$

$$f_t = \frac{\pi d}{.3} \cdot \frac{RPM}{60}$$

PFL at NL = $K_1 K_2 K_3 K_4 K_5 K_6$ (Bore Area)

$K_1 = 7.0$

K_2 = fn (B_g) = .8 for 45 Kilolines/in^2 gap density

$$K_3 = \text{fn}\,(f_T)\;1.65) = \text{fn}\left[\frac{\pi d}{.3}\;\frac{(\text{RPM})}{60}\right]^{1.65}$$

$$K_4 = \text{fn}\,(\tau_s) = .175$$

$$K_5 = \text{fn}\,\left(\frac{b_s}{g}\right) = 1.45$$

$$K_6 = \text{fn}\,(C_1) = .22$$

PFL at NL $= (7.0)\;.8\;(K_3)\;(.175)\;1.45\;(.22)$ (Bore Area)

$= .313\;K_3$ (Area) for Bg = 45 Kilolines/in^2

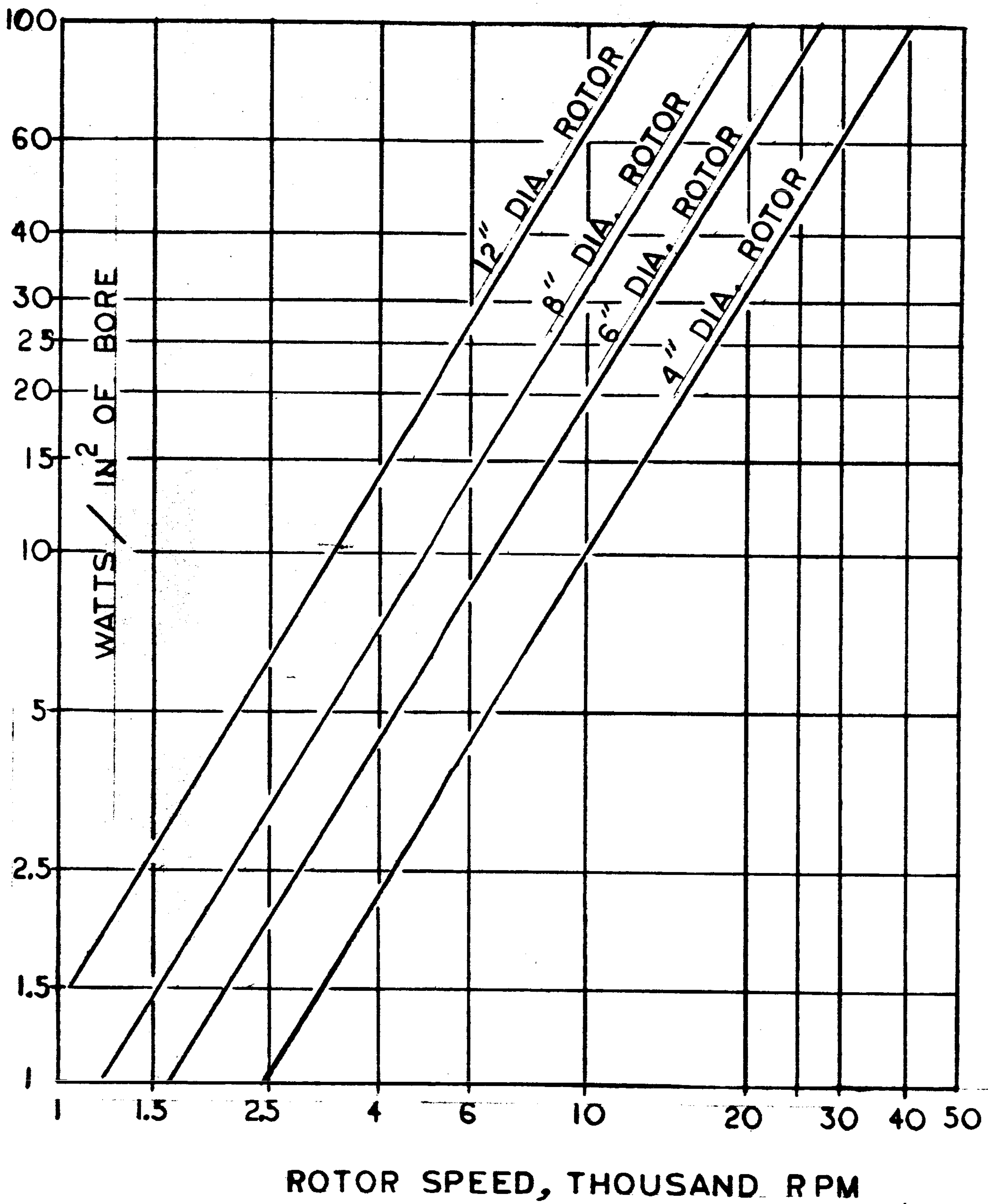
$= .235\;K_3$ (Area) for Bg = 40 Kilolines/in^2

$= .11\;K_3$ (Area) for Bg = 30 Kilolines/in^2

$= .039\;K_3$ (Area) for Bg = 20 Kilolines/in^2

Rotor Dia. In.	RPM	No-Load Pole Face Loss in Watt/in^2 $\tau_s = .3$			
		Bg = 45	Bg = 40	Bg = 30	Bg = 20
4	2,000	.72	.54	.25	.09
"	4,000	2.28	1.7	.8	.284
"	8,000	7.2	5.4	2.5	.9
"	12,000	14.1	10.6	4.9	1.76
"	24,000	44	33	15.4	5.5
"	48,000	128	96	45	16
6	2,000	1.4	1.05	.49	.17
"	4,000	4.4	3.3	1.54	.55
"	8,000	14	10.5	4.9	1.75
"	12,000	27	20.2	9.5	3.37
"	24,000	86	64.5	30	10.7
"	48,000	272	204	95	34

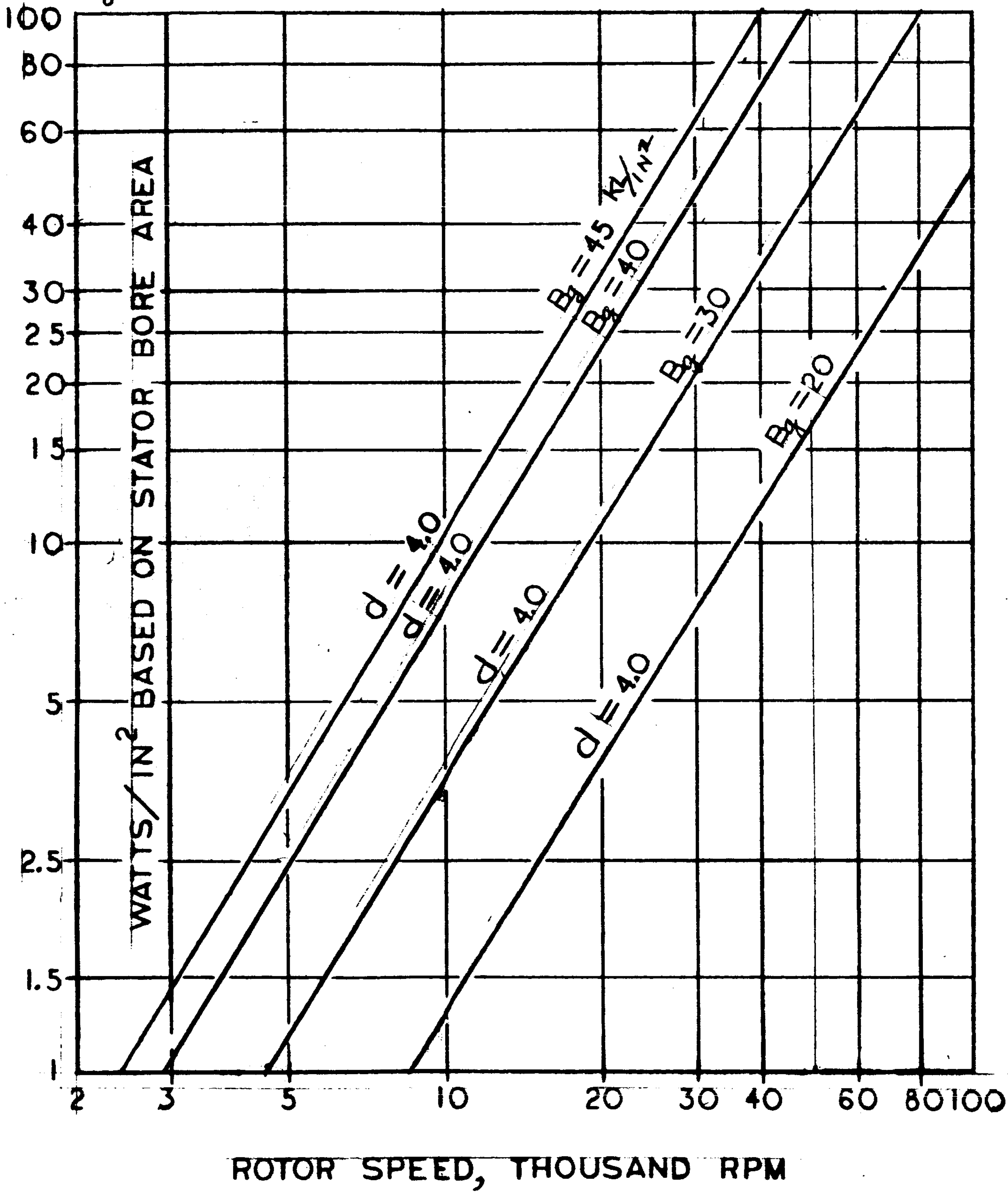
POLEFACE LOSSES IN A SOLID POLEFACE AT NO LOAD AS A FUNCTION OF SPEED WHEN THE GAP DENSITY $B_g = 45\ KL/IN^2$
$b_s/g = 2.0$ SLOT PITCH $\tau_s = .30$



CURVE

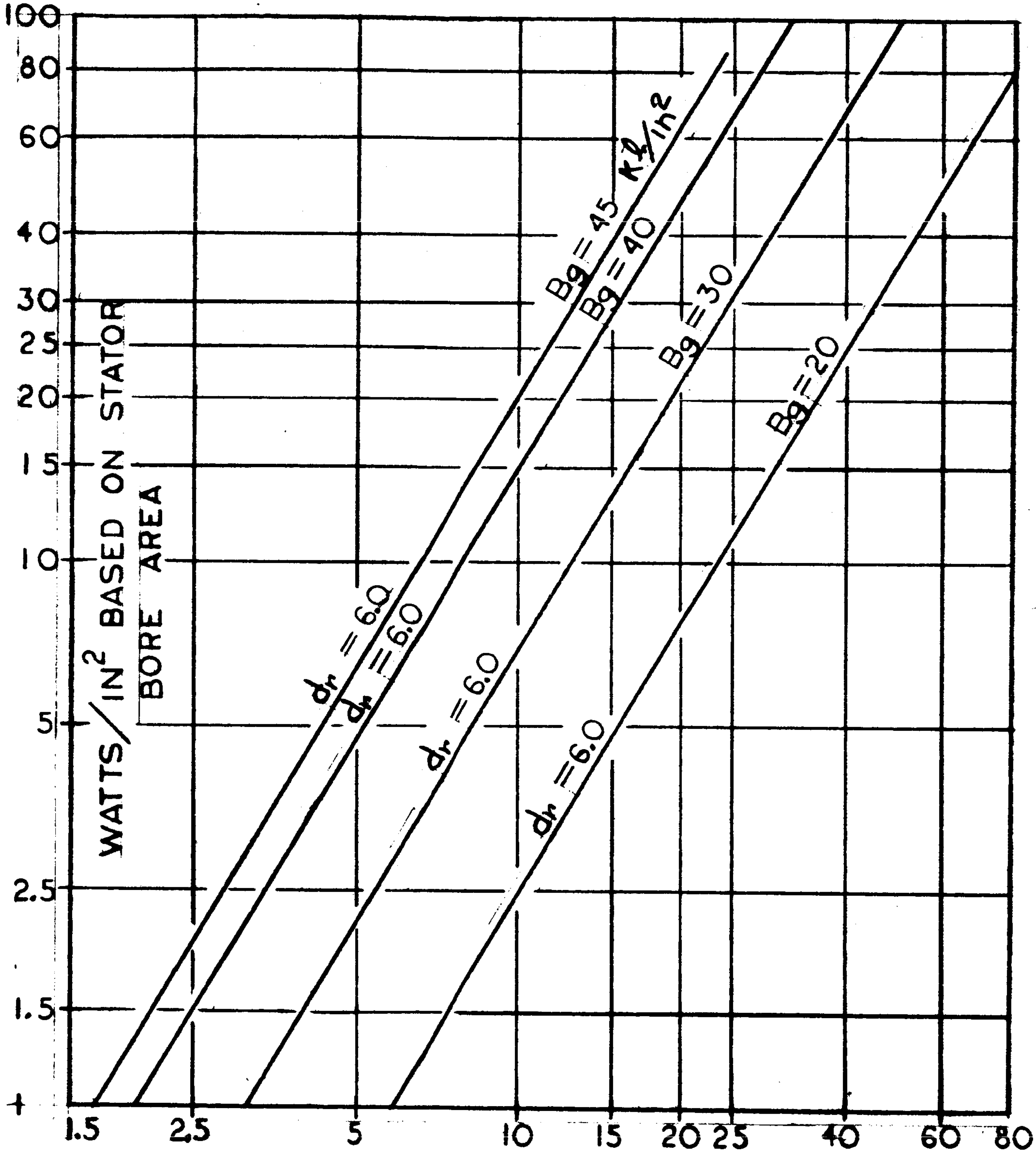
POLE FACE LOSSES IN A SOLID POLE FACE AT NO LOAD AS A FUNCTION OF SPEED AND AIR GAP DENSITY FOR A 4.0 DIA. ROTOR.

$\frac{b_s}{g} = 2.0$ SLOT PITCH = $\tau_s = .30$



CURVE

POLEFACE LOSSES IN A SOLID POLEFACE AT NO LOAD
AS A FUNCTION OF SPEED AND AIR-GAP DENSITY
FOR A 6.0" DIA. ROTOR. $b_s/g = 2.0$ SLOT PITCH, $\tau_s = .30$



CURVE

DISSIPATING THE POLE FACE LOSSES

If the pole face losses are to be dissipated to gas similar to air or if the machine is force ventilated with air, the best coefficient that could be expected is 0.10 watts/in^2 of surface/^{o}C rise above the air. See curve from Luke and curve from A.D. Moore.

If 25 watts/in^2 is to be dissipated from the rotor surface, the temperature rise of the rotor surface in this case will be $\frac{25}{.10} = 250^oC$ above the cooling air or gas. Similarly, if 50 watts/in^2 must be dissipated, then the temperature rise of the rotor will be 500^{o}C above the cooling air.

If room temperature cooling air can be used in sufficient quantity, 40 watts/in^2 might possibly be dissipated from the generator rotor surface. If a heat transfer coefficient of .10 w/in^2/^{o}C can be obtained, the rotor temperature will be approximately 800^{o}F or 425^{o}C.

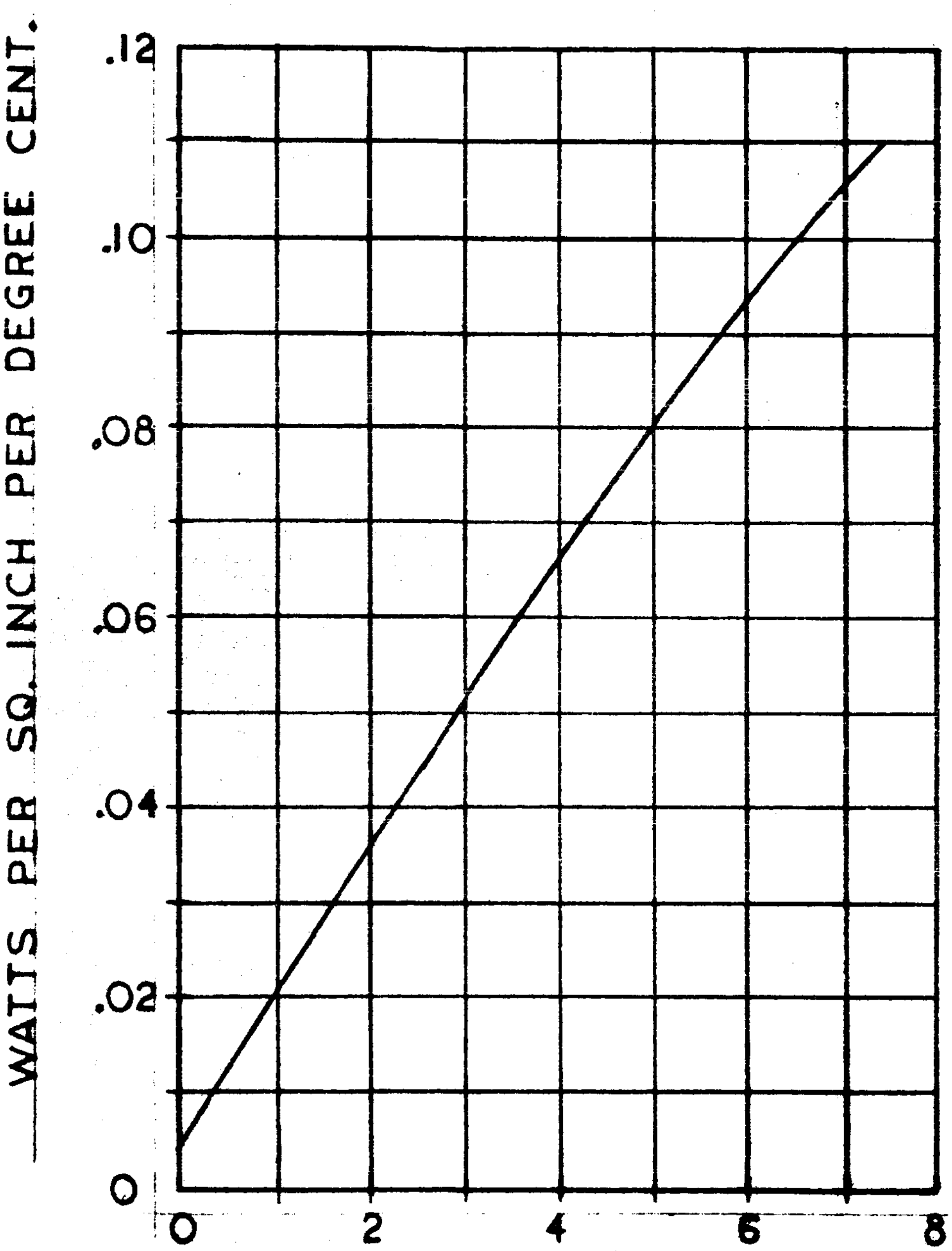
A cooling coefficient more likely to be obtained is .08 watts/in^2/^{o}C and this value has been used on curve to show probable rotor temperatures associated with various no-load pole face loss levels.

EFFECT OF REDUCING GAP DENSITY

If a high-speed generator is designed and the PF losses are too great at say 45 kilolines/in^2 air gap density, reducing the flux density will reduce the pole-face, no-load losses by the ratio of gap densities raised to the power 2.5. The factor for gap density is K_2.

Bg	K_2
20	.10
25	.18
30	.28
40	.6
45	.8

SURFACE HEAT DISSIPATION FROM A GENERATOR ROTOR.



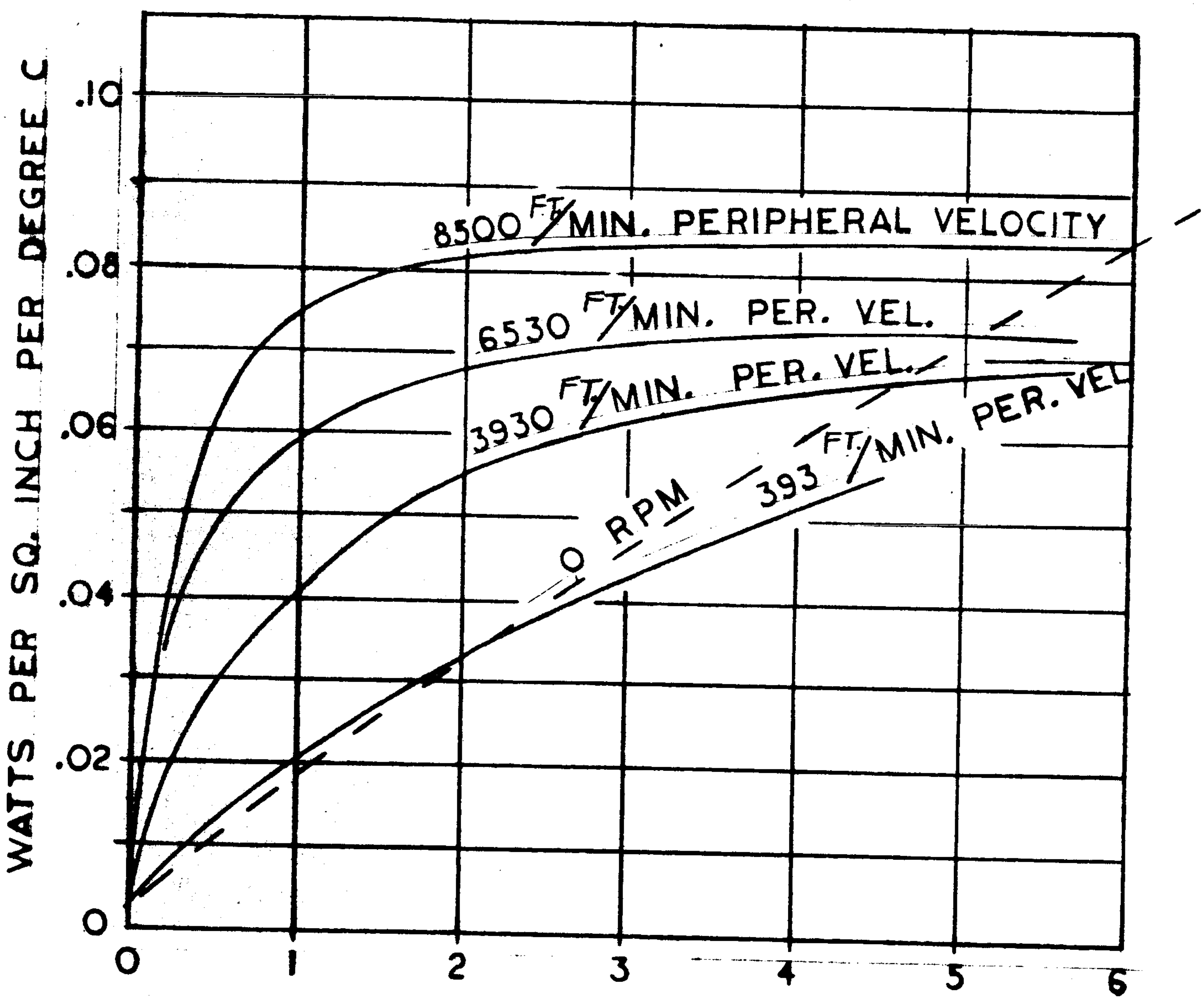
AVERAGE AIR VELOCITY THROUGH MACHINE IN THOUSANDS OF FEET PER MINUTE.

FROM LUKE: HEATING OF RAILWAY MOTORS. AIEE TRANS 1922 VOL 41 PP 165-173.

CURVE

WATTS DISSIPATED FROM THE ROTOR OF AN ELECTRICAL MACHINE WHEN FORCED-AIR COOLING IS USED.

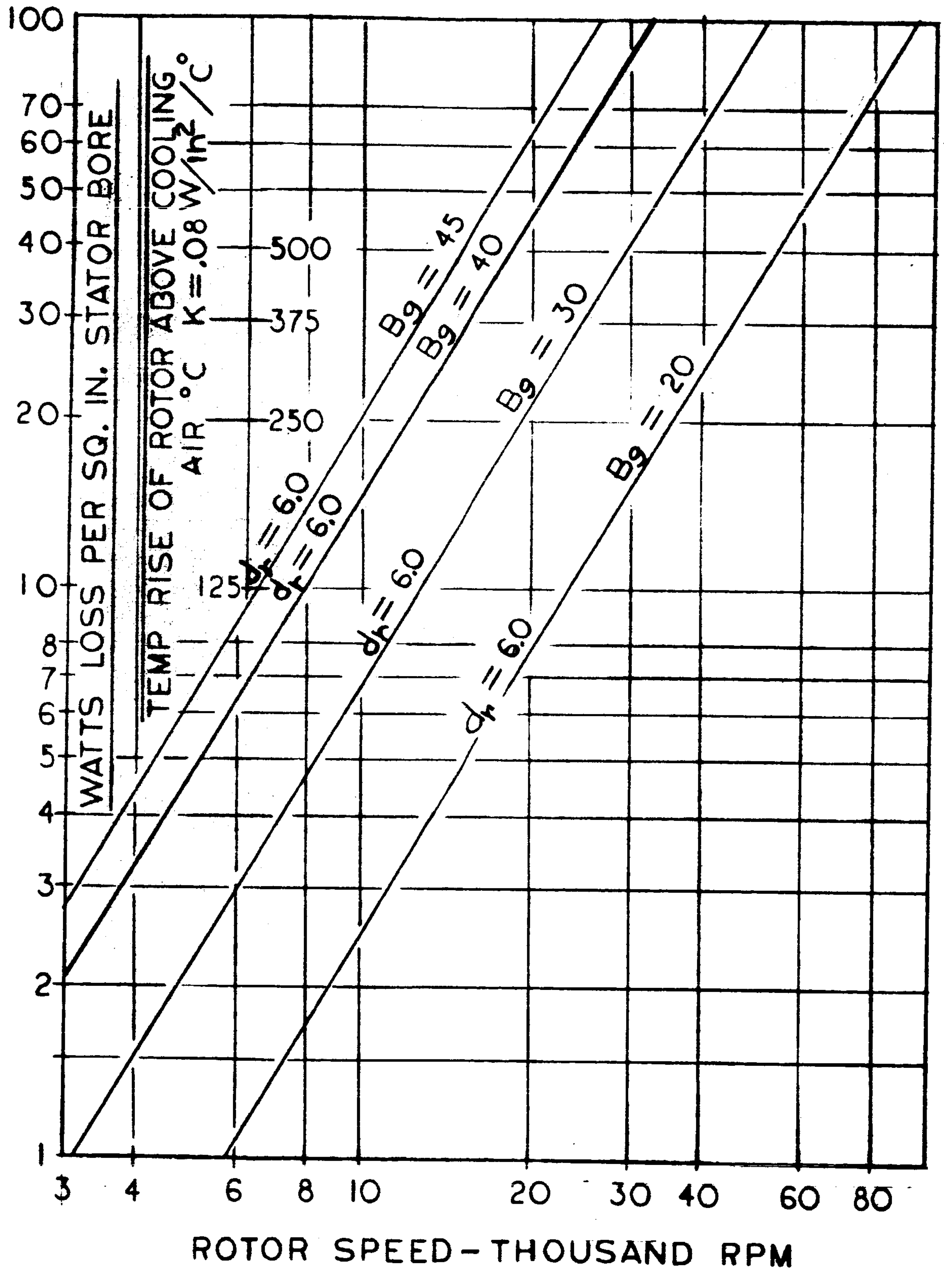
FROM A.D. MOORE: FUNDAMENTALS OF ELECTRICAL DESIGN. McGRAW HILL 1927 PAGE 134.



AVERAGE COOLING AIR VELOCITY THROUGH THE MACHINE AIR-GAP – THOUSANDS OF FEET PER MINUTE.

CURVE

NO LOAD POLE FACE LOSSES FOR A SOLID-ROTOR GENERATOR HAVING 6.0 DIA. ROTOR AND A TOOTH PITCH OF .3" $b_s/g = 2.0$



CURVE

EFFECT OF VARYING SLOT PITCH

When the slot pitch is varied, the pole face loss varies as the slot ripple frequency variation raised to the 1.65 power and varies as the tooth pitch variation raised to the 1.26 power. The no-load pole-face loss will decrease as the tooth or slot pitch is increased.

The net change in the loss as the slot pitch increases is approximately (ratio of slots)$^{1.65}$ (ratio of slot pitches)$^{1.26}$.

In the tabulation for diameter = 4.0", Bg = 40 Kl/in^2, $_s$ = .3", RPM = 12000, the NLPFL = 10.6 watts/in^2 of stator bore.

If the slot pitch is increased to .6", the NLPFL will be reduced to 8.1 watts/in^2 of stator bore area.

EFFECT OF SLOT OPENING

Completely closing the slots can have only limited effect in reducing pole face losses since the bridge closing the slot must saturate before the machine can operate. The saturated bridge represents an effective opening in the slot and the ratio $\frac{b_s}{g}$ is some definite value. In considering the effect of closing the slot with a bridge, a smaller effective opening can be assumed such as $\frac{b_s}{g}$ = 1.0. The pole face loss at no load varies approximately as the ratio

$$\left(\frac{\frac{b_{s2}}{g}}{\frac{b_{s1}}{g}}\right)^{1.3} = \left(\frac{b_{s2}}{b_{s1}}\right)^{1.3}$$

So, by reducing the slot opening to 1/2 its original width, the no-load losses can be reduced to about 1/2.4 of the initial no-load value. <u>This applies to the no load losses only and the pole-face losses under load may be much higher because of the reduced slot opening</u>. Load losses in the pole-face are a function of the stator loading and of the slot opening to air gap ratio (bs/g). This can be expressed as a function of bs/g and a function of (Xad)^2.

LOAD LOSSES IN THE POLE FACE

Under load, the pole face losses are increased. This increase is due to the armature mmf wave and resulting flux wave which has a saw tooth shape.

The higher the current loading in the stator, the more pronounced the saw tooth shape of the flux wave becomes when the machine is fully loaded. This effect is a function of the ratio -

$$\left[\frac{\text{series conductors/slot} \times I_{ph}\, K_{sc}}{\text{no load air gap ampere turns}}\right]^2 \quad \text{(NLPFL)}$$

where K_{sc} is a modifying factor describing the effect of $\frac{b_s}{g}$. The smaller the opening, the sharper the step or saw-tooth in the armature reaction flux wave.

E.I. Pollard treated the pole face load losses in his paper "Load Losses in Salient Pole Synchronous Machines", AIEE Trans., Vol. 54, 1935, pp 1332-1340. His work shows that if the slot opening to air gap ratio is made too small, the result may be an increase in total pole face losses. See curve

In the rotor sizes 4.0" dia. to 8.0" dia., an air gap length of .030" is reasonable to assume. If the following values are assumed:

ampere loading = 900 ampere wires per inch of stator bore periphery, bs/g = 2.0, Bg = 40 Kl/in^2, then the air gap ampere turns are about 400 and from curve

$$\text{PF load losses} = \left[\frac{K_{sc}\, I_{ph}\, N_s}{\text{AGAT}}\right]^2 \quad \text{NLPFL}$$

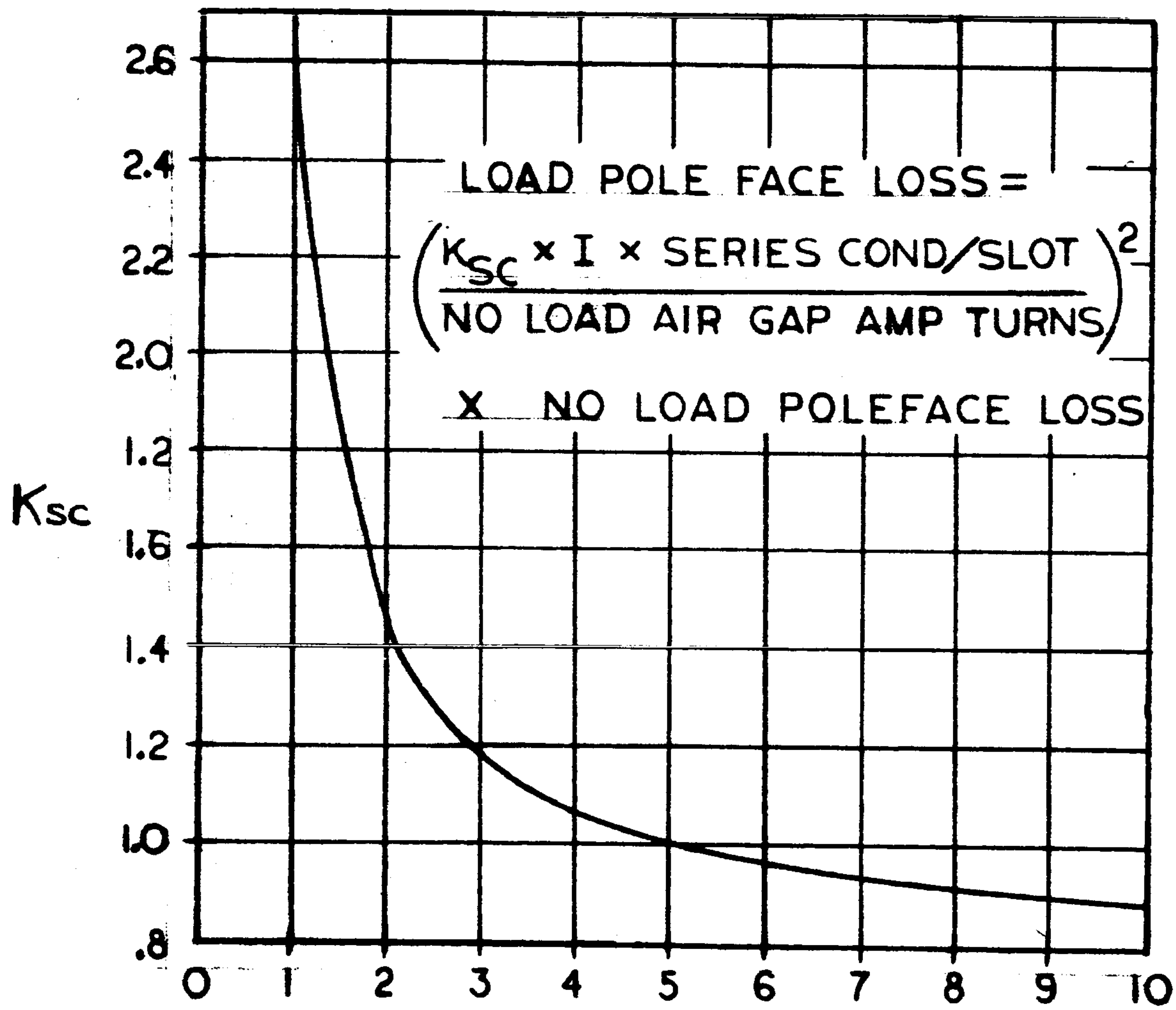
$$= \left[\frac{1.4\ (270)}{400}\right]^2 \quad \text{NLPFL}$$

PF Load Losses = .91 x no load PF losses

where N_s = conductors/slot

$I_{ph}\, N_s$ = 900 x .3 = ampere wire loading x slot pitch

LOAD LOSSES IN THE POLE FACE
FROM E.I. POLLARD: LOAD LOSSES IN
SALIENT POLE SYNCHRONOUS MACHINES,
AIEE TRANS. VOL. 54 1935 PP 1332 1340.

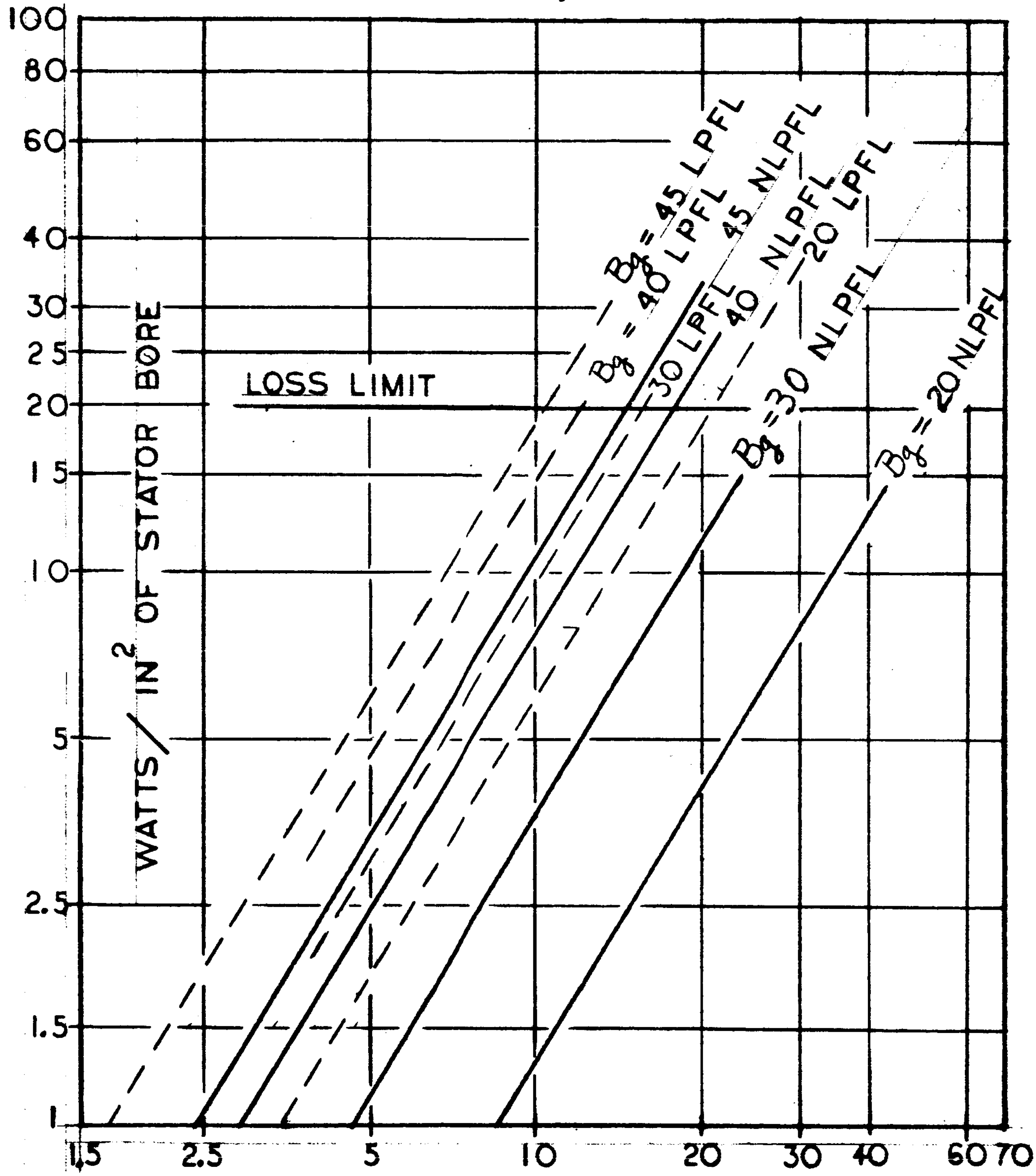


b_s/g b_s = SLOT OPENING
g = AIR GAP LENGTH

CURVE

SOLID POLE FACE

POLE FACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 4.0" DIA. ROTOR AT VARIOUS GAP DENSITIES. A=900 $b_s/g = 2.0$ $\tau_s = .3$

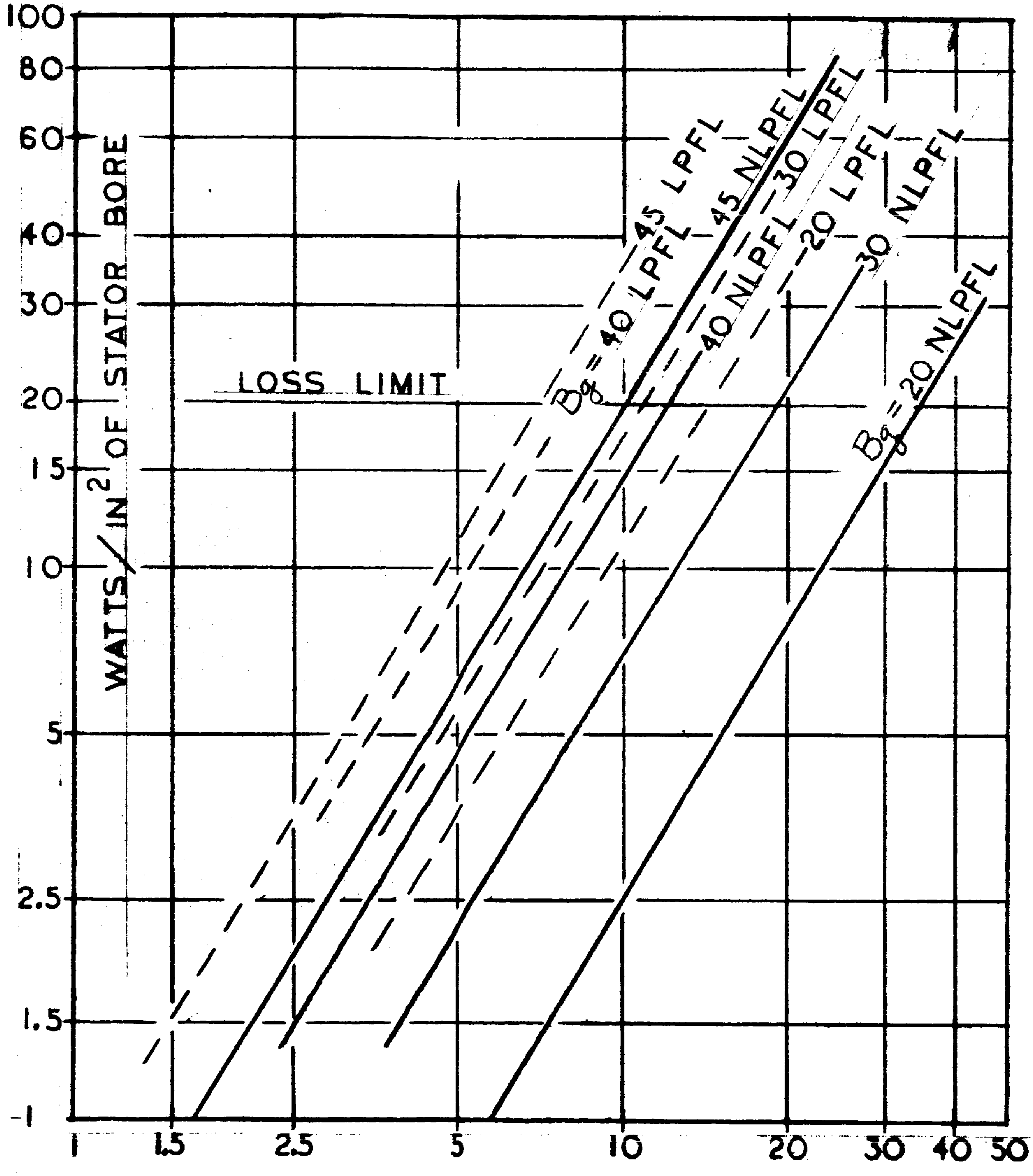


CURVE

SOLID POLE FACE

POLE FACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 6.0" DIA. ROTOR AT VARIOUS GAP DENSITIES.

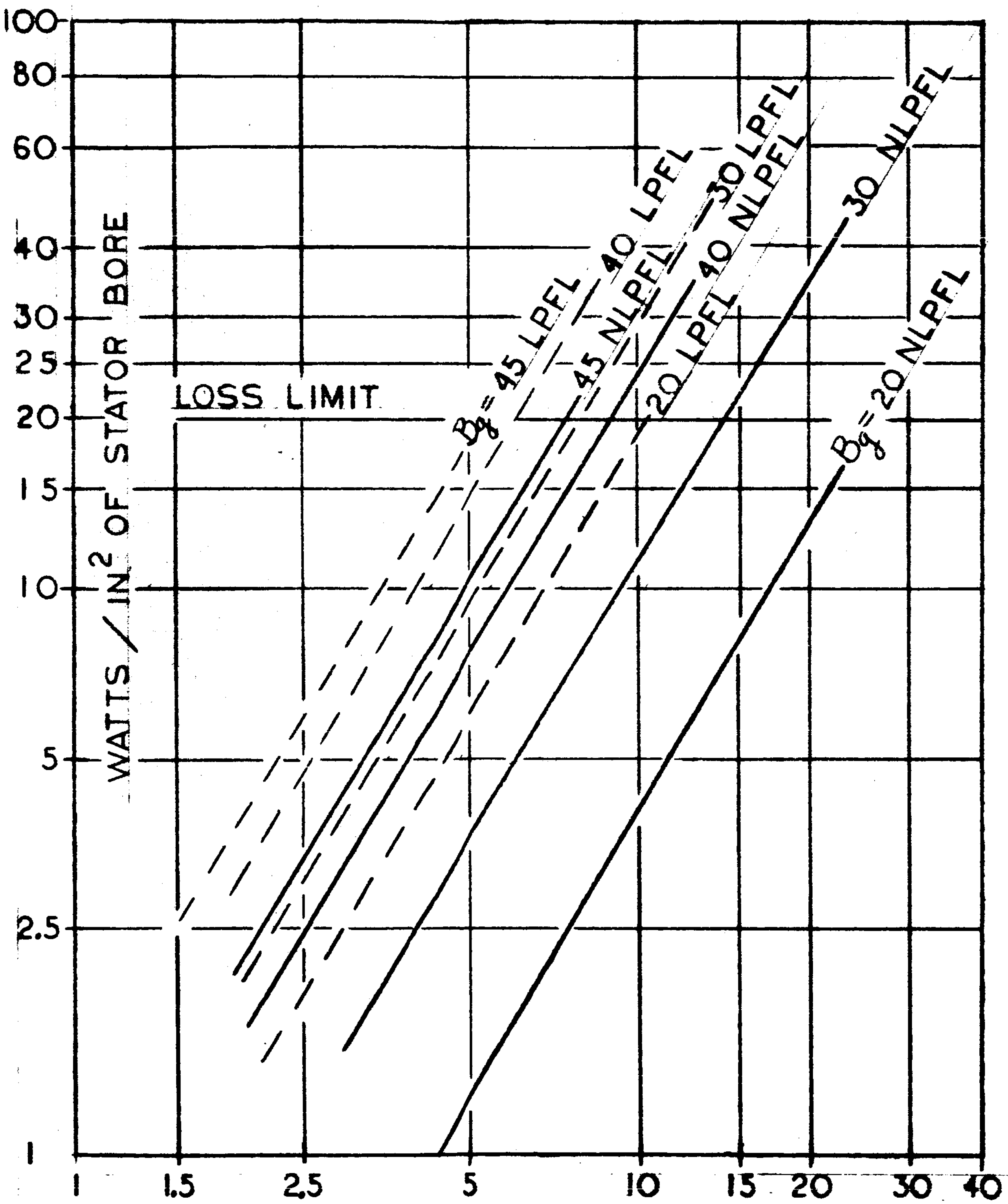
A=900 $b_s/g = 2.0$ $\tau_s = 3$



CURVE

POLEFACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 8.0" DIA. ROTOR AT VARIOUS GAP DENSITIES

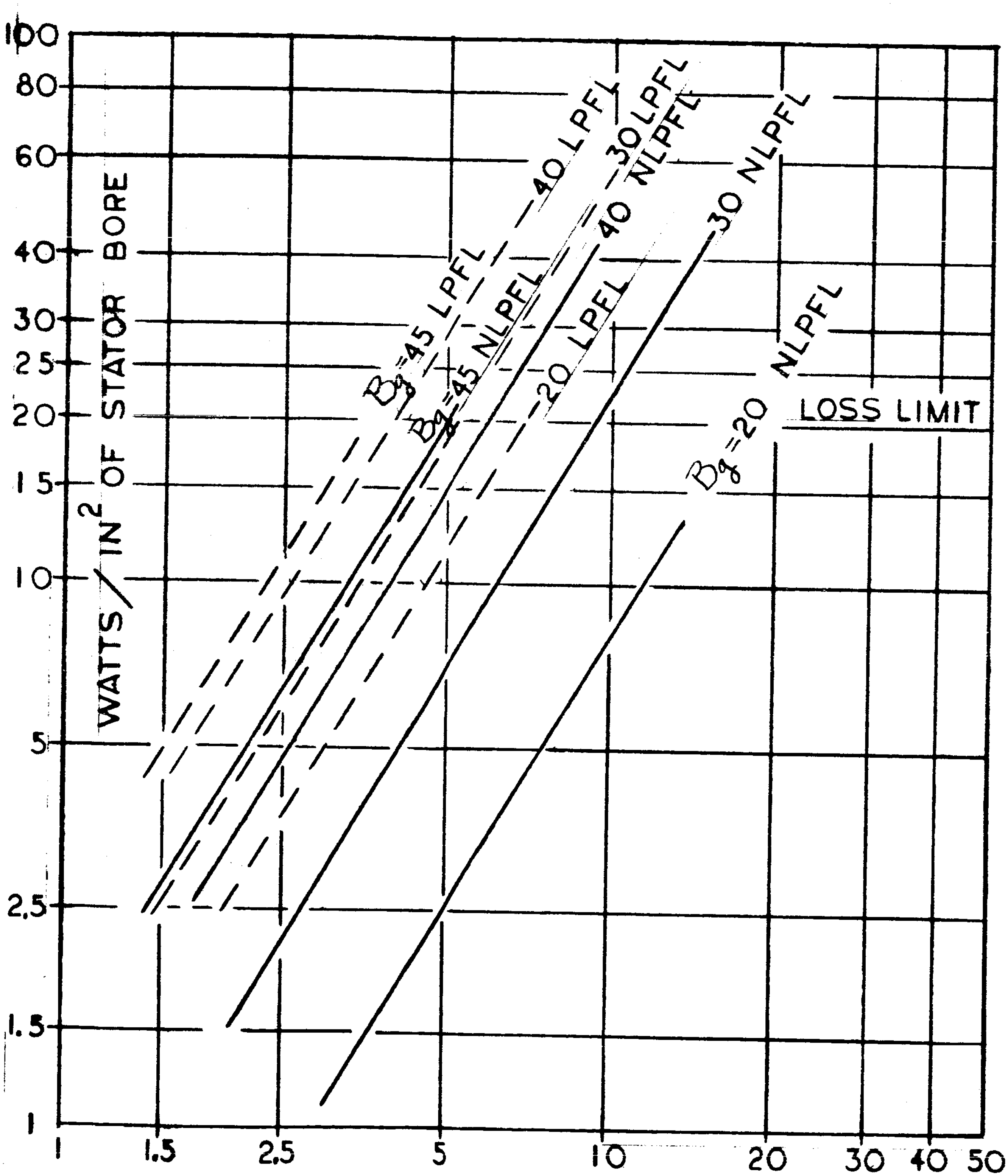
GAP DENSITIES: A=900, $b_s/g = 2.0$, $\tau_s = .30$



CURVE

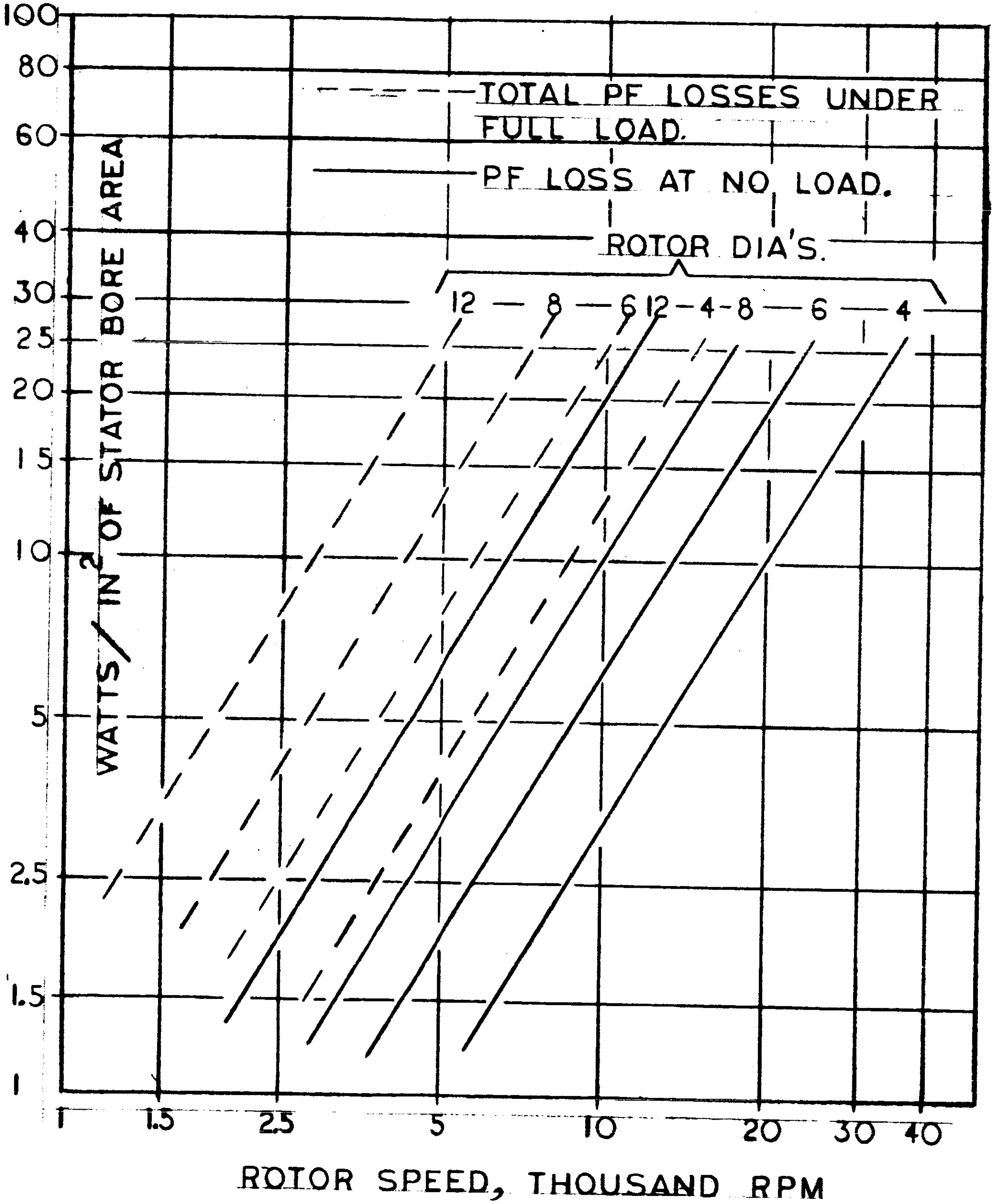
SOLID POLE FACE

POLE FACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 12.0" DIA. ROTOR AT VARIOUS GAP DENSITIES. A=900 $b_s/g = 2.0$ $\tau_s = .30$



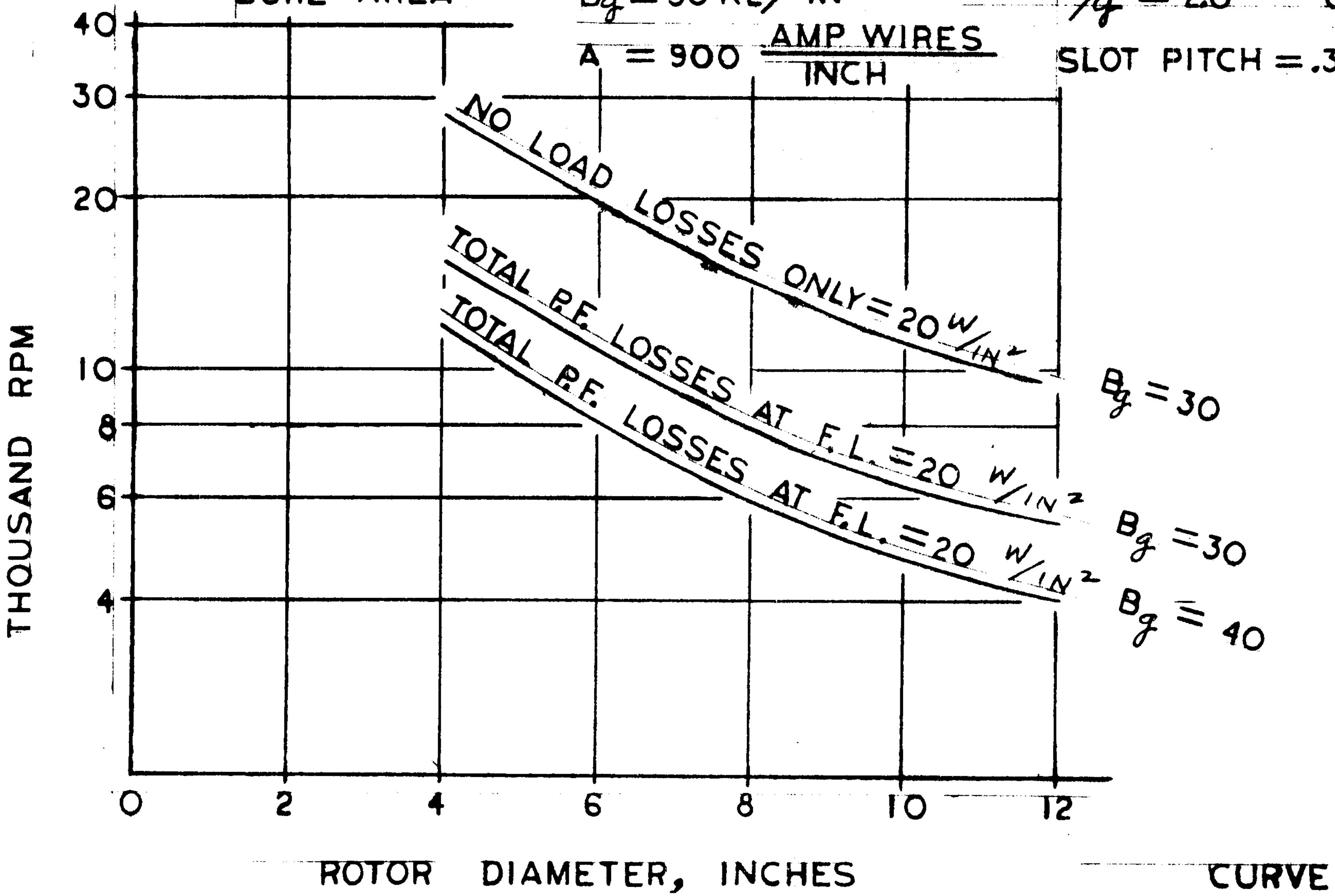
CURVE

POLEFACE LOSSES AT NO LOAD AND AT FULL LOAD FOR ROTORS OF VARIOUS DIAMETERS $B_g = 30$ KL/IN^2
$\bar{A} = 900$ AW/IN SLOT PITCH = .4 $b_s/g = 20$

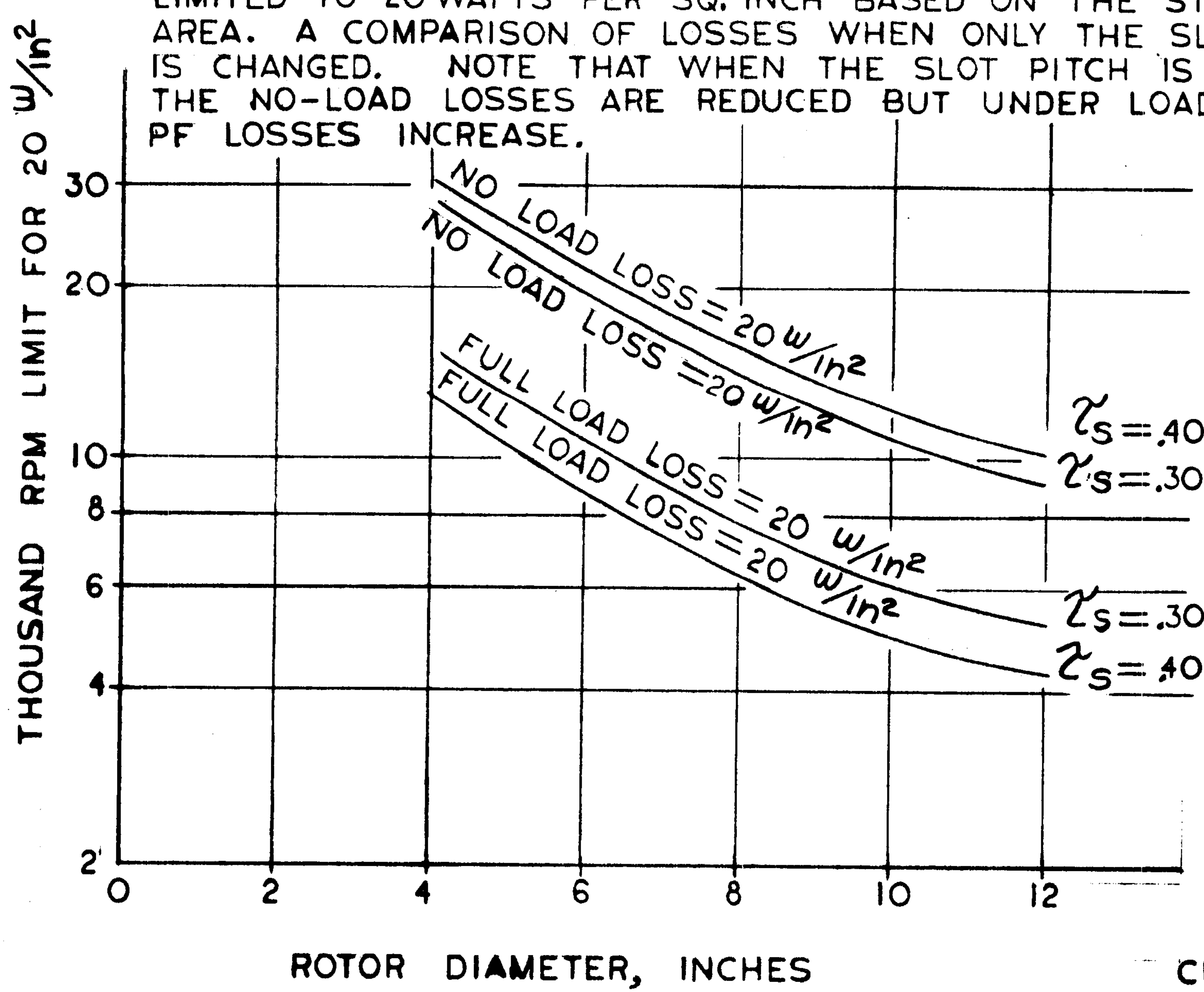


CURVE

ROTOR DIA. VS ROTOR SPEED FOR SOLID POLE FACE ALTERNATORS LIMITED TO 20 WATTS / IN² POLE FACE LOSSES BASED ON STATOR BORE AREA



ROTOR DIA. VS ROTOR SPEED FOR SOLID POLE FACE ALTERNATORS LIMITED TO 20 WATTS PER SQ. INCH BASED ON THE STATOR BORE AREA. A COMPARISON OF LOSSES WHEN ONLY THE SLOT PITCH IS CHANGED. NOTE THAT WHEN THE SLOT PITCH IS INCREASED THE NO-LOAD LOSSES ARE REDUCED BUT UNDER LOAD THE TOTAL PF LOSSES INCREASE.



CURVE

AGAT ~~= 400~~ = ~~ampere turns drop across main air gap~~

K_{sc} = loss factor from curve

The pole-face load losses are added to the no-load pole-face losses.

When the air gap density is decreased, the ampere turns drop across the air gap decreased in direct proportion and the pole-face load losses increase as the square of the change in gap density. For example, the factor just calculated above for a 40 Kl/in^2 gap density was .91 (NLPFL). When the gap density in the same machine is reduced to 30 Kl/in^2 but the ampere loading is maintained at 900 AW/in^2, the loss eqn. becomes -

$$\text{PFLL} = \left[\frac{1.42\ (270)}{300}\right]^2 \ \text{NLPFL} = 1.63\ (\text{NLPFL})$$

$$\text{or PFLL} = \left(\frac{4}{3}\right)^2 \ (.91)\ \text{NLPFL} = 1.63\ (\text{NLPFL})$$

We have already discussed how the reduction of the air gap flux density reduces the pole face no load loss per square inch of stator bore area by $\left(\frac{B_{g2}}{B_{g1}}\right)^{2.5}$ and in the case of a reduction from 40 Kl/in^2 to 30 Kl/in^2 the reduction in NLPFL is $\left(\frac{3}{4}\right)^{2.5} = .488$.

The full load PFL increased by $\left(\frac{4}{3}\right)^2$ or 1.78 so the total load loss was reduced from 1.0 to 1.78 (.488) = .87 a reduction of 13%.

SLOTTING THE ROTOR TO REDUCE THE POLE-FACE LOSSES

Figure 1 shows graphically what happens when a solid pole-face is slotted to reduce pole face losses, when the slot approximates 50% of the pole surface.

Assuming that the air gap flux density is unity, the initial pole face density at its surface was also unity.

When the rotor was slotted to the extent that 50% of the surface was removed, the density in 1/2 the remaining surface or 1/4 of the initial surface became 1.74 times the initial value or 1.74 per unit. The surface density in the remaining 1/4 of the initial surface increased to 2 times the surface density or 2.0 per unit. The average increase in total pole face losses based upon the increase in gap density at the surface of the pole is 2.4 times. However, the increased air gap density in the region of the pole surface reduces the effect of the slot ripple and tends to reduce the load losses. These effects can nearly enough offset the effect of grooving to make the pole face losses about the same with or without grooving.

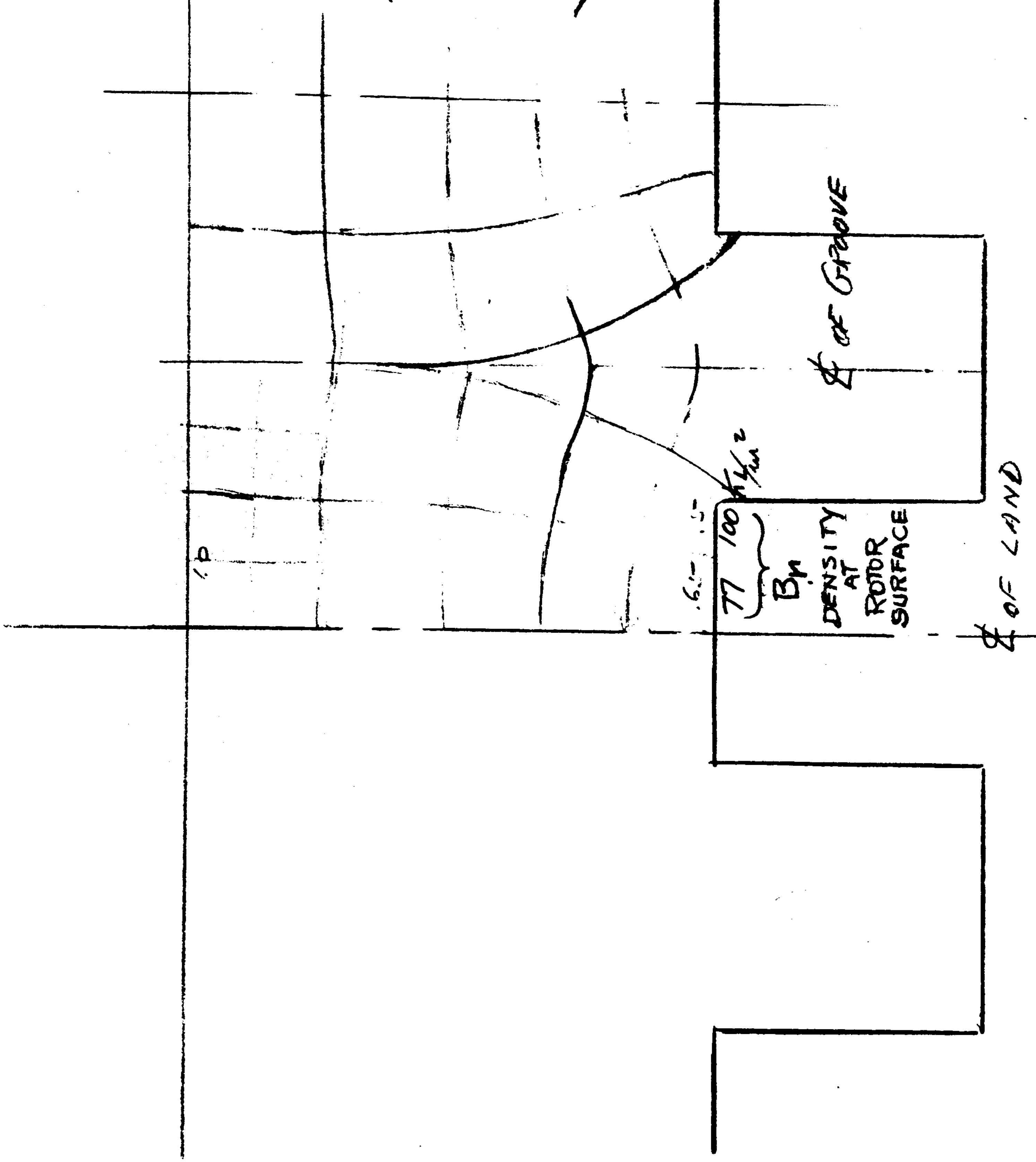
Experiments made in support of this study showed insignificant results when the rotor was grooved approximately with .020-.03 wide grooves, and only 50% of the initial surface was left.

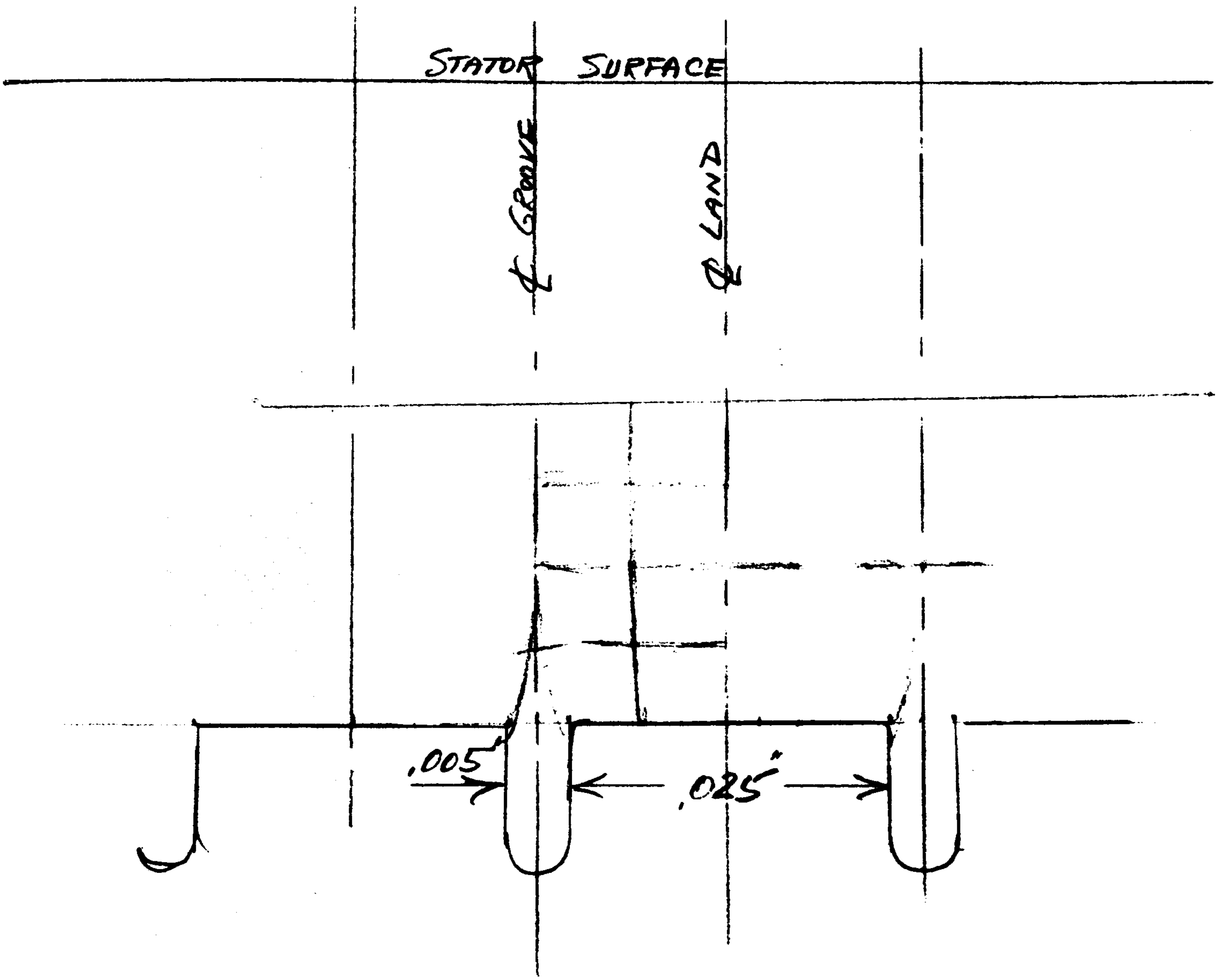
Figure shows the results obtainable when the rotor grooving is about 10 to 12 % of the surface area. This amount of grooving does not change the rotor surface flux density a significant amount. To realize a satisfactory reduction in pole face losses, the lands formed by the grooving should be thin; .020" width is a good maximum for 400 cps generators.

To satisfy the requirement for lamination-thickness lands, and only 12% loss of surface, the grooves should be only about .0025" wide and the requirement for such an extremely narrow slot imposes a difficult manufacturing problem. Some methods that can be used to cut the narrow grooves are: diamond sawing with narrow saw or wire, electric-discharge machining with small diameter wire used as electrodes, and electron-beam machining.

DISTRIBUTION OF SURFACE FLUX DENSITIES WHEN A ROTOR POLE HEAD HAS 50% OF ITS SURFACE GROOVED

GAP DENSITY = 50 KL/IN²





WITH .025" LANDS AND .005 SLOTTING, THE POLE SURFACE DENSITY IS 109% THAT OF A SMOOTH POLE FACE

USING SYNCHRONOUS GENERATORS AS MOTORS

INTRODUCTION

When an electric power generator is driven from a turbine in a nuclear reactor energy conversion loop, the motoring characteristics of the generator are an important consideration in the system design.

All of the nuclear reactors that are to be used in Space (The SNAP Systems) are to be started after they are in orbit or after they are outside the earth's atmosphere. This is planned to reduce the danger of atmosphere contamination in case of a launch failure. To start the reactor, or to make it go critical, the controls operate to allow the fuel assembly emission to increase and, at the same time, the coolant or working fluid is circulated to prevent the fuel assembly from overheating.

In a Brayton Cycle Conversion system, the power output turbine can be used to circulate the coolant gas or working fluid through the fuel assembly until the gas is heated and the cycle is self-sustaining.

An alternate start-up method for Brayton Cycle systems uses the release of bottled gas to introduce the working fluid into the piping and, at the same time, force the gas through the reactor where the gas is heated. In this way, the cycle is started and it becomes self sustaining. This second method must work perfectly and the reactor must heat up the first time because there is no second try.

In contrast, the turbine used as a pump can circulate the gas and allow the reactor to heat up slowly if necessary. Using the generator as a motor allows margin in the start up procedure. The margin increases the reliability of the system.

INTRODUCTION - Continued

In Rankine Cycle systems that use two liquids, one pump may be on the generator shaft or both pumps may be on the generator shaft. In either case, the generator must be operated as a motor to circulate the working fluids and prevent the fuel assembly from overheating during the start-up period.

An alternate start-up method for Rankine Cycle systems can use pumps that by-pass the turbine-generator shaft-driven pumps. This complicates the system and tends to reduce the reliability.

In either Brayton Cycle systems or Rankine Cycle systems, the motoring characteristics of the generator are of great interest.

USING SYNCHRONOUS GENERATORS AS MOTORS

IN BRIEF

Synchronous generators can be started as induction motors and operated as synchronous motors. The following discussion explains motor operation of the two types of synchronous generators; wound-pole and solid-rotor.

DISCUSSION

General

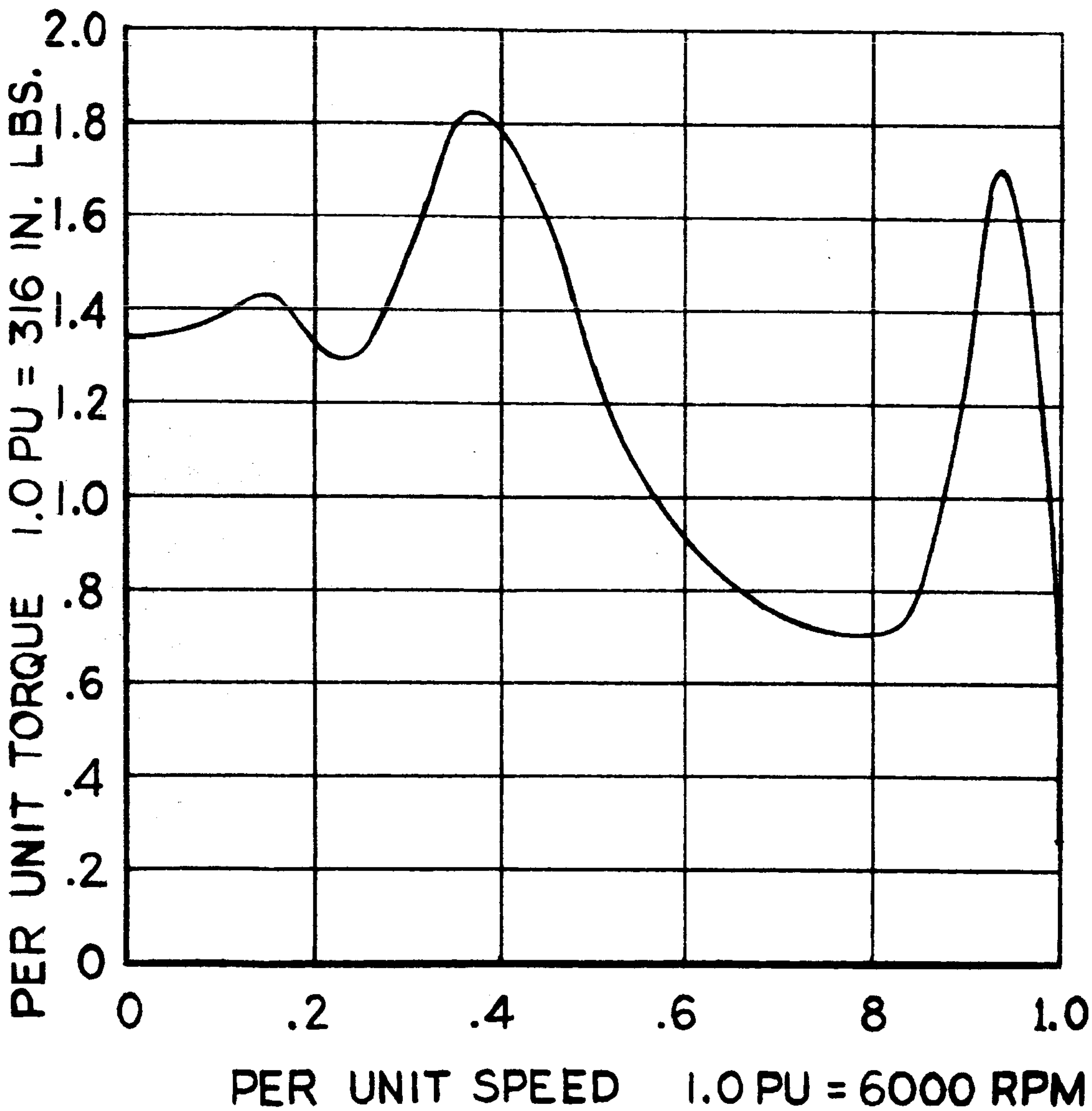
The rotating electrical generator converts mechanical energy to electrical energy. Electric motors convert electrical energy to mechanical energy. There is no basic difference in the two classes of machines as one machine can be designed to operate reversibly - as a motor or as a generator.

If the synchronous generator is used as a motor, it can operate either as a synchronous motor or as an induction motor. An induction generator can be motored only as an induction motor. The two modes of electrical motor operation are, then, synchronous and induction.

When the synchronous generator operates as a synchronous motor, it can be brought into synchronism by starting it as an induction motor until its speed is near synchronism and then applying field current to the d-c fields to accelerate the rotor to synchronous speed. It can also be started in synchronism by slowly varying the voltage and frequency from a low voltage level and low frequency to the rated values. This latter method is called a full synchronous start and throughout this kind of start, the synchronous motor can produce rated torque at rated current. Since the full synchronous start requires special supply equipment, it is not often used.

A salient-pole wound-field synchronous generator can be, and usually is, made with a pole face winding that is essentially an induction motor cage winding. This winding is called an amortisseur or damper winding. Its primary purpose

SPEED-TORQUE CHARACTERISTIC OF A
WOUND-POLE, SALIENT-POLE, SYNCHRONOUS,
GENERATOR HAVING A COPPER CAGE
WINDING. FIELD WINDINGS ARE SHORTED.
NO SKEW IN STATOR OR ROTOR



GENERATOR IS 30 KVA, .75 PF, 400 CPS,
6,000 RPM. P.U. BASE IS 22.5 KW.

in a generator is to damp out rotor oscillations and negative sequence flux waves. The same cage winding is well suited for induction motor operation and can sometimes be made as a double cage winding for higher starting torque combined with low slip.

The synchronous motor with the damper winding (or squirrel cage pole face winding) can have about the same speed-torque characteristics as an induction motor. The important difference is that the cage winding is much smaller than it would be if the motor were a normal induction motor, and the operating cycle must be short because of the small cage bars. Large synchronous motors are frequently limited to two successive starts after which a cooling period of about 30 minutes must be allowed before another start is attempted. This is in contrast to the continuous full-load operation of a normal induction motor.

Speed-Torque Characteristic of Salient-Pole Machine

The speed-torque characteristics of a 30 KVA salient-pole, synchronous generator operating as an induction motor is shown in Curve 1. This generator shows cusps in the speed torque curve that can be removed by skewing the stator one slot pitch.

Per-Unit Base

The speed-torque curves in this discussion are plotted on a per-unit scale with the generator nameplate kilowatt rating used as the 1.0 P.U. base. The 30 KVA, .75 PF machine tested has a KW rating of 22.4 KW.

1.0 P.U. torque is then $T = \dfrac{(84300)\ (22.5)}{6000} = 316$ in. lb.

$$\text{Torque in inch pounds} = \frac{84300\ (\text{Kilowatts})}{\text{RPM}}$$

Such a base is meaningful. A machine designed for low power-factor loads has lower reactances than a machine designed for the same output at a high power factor. The per unit torque of a low reactance motor is higher than that of a high reactance motor.

Induction Motor Characteristics

The starting and speed-torque characteristics of an induction motor can be varied over a wide range by changing the resistance of the rotor winding. Wound-rotor induction motors are made with insulated polyphase rotor windings. These windings connect to slip rings on the shaft and variable external resistance can be added to the rotor windings. By varying these resistances, the maximum torque point on the speed-torque curve can be varied from zero speed to around 98% speed. Synchronous motors have been made with insulated, wound, pole face windings connected through slip rings to external starting resistances. Such motors are special and seldom used.

When the rotor resistance of an induction motor is changed, the speed torque characteristics curve does not change in shape. The maximum torque point and all other points shift to a new slip point. The change is proportional to the change in resistance. If the resistance of the rotor is doubled, all of the points of the speed-torque curve shift to new slip values twice that of the original. Curve 2 illustrates this change.

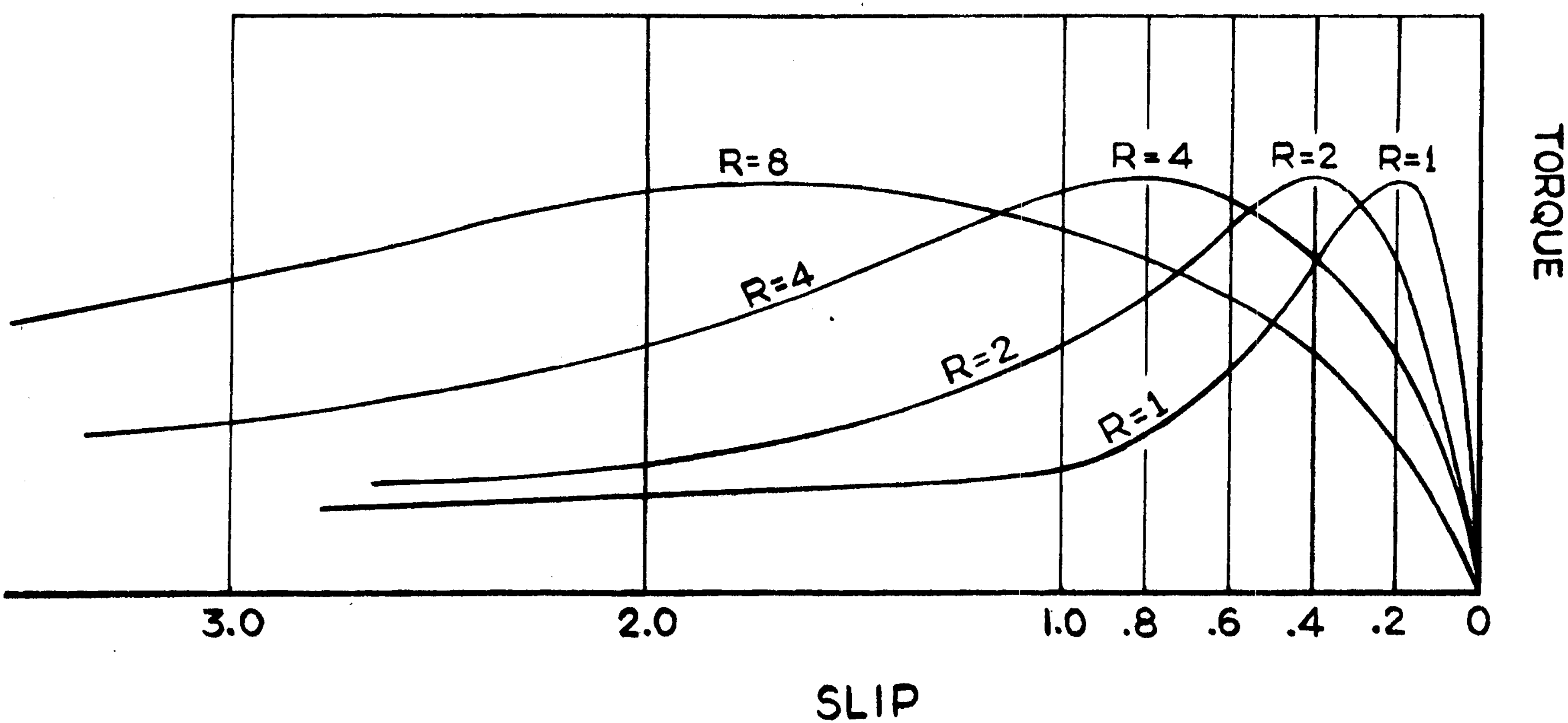
The characteristic curve shown for rotor resistance $R = 1$ is approximately that of a normal low-slip motor. The characteristic curve shown for $R = 4$ is for a high slip motor and could represent a torque motor.

A motor designed to give high torque against a load driving it in the reverse direction might have the characteristic shown for $R = 8$.

If a synchronous motor having a cage winding is to start under load and synchronize, it may be required to have high starting torque and low slip. A low slip motor will produce its maximum torque at 95% to 98% of synchronous speed.

To pull into synchronism, a synchronous motor must be operating at 95% speed or more when the field current is applied. The torque resulting from the attraction between the moving stator flux wave and the flux from the wound

TORQUE - SLIP CURVES OF AN INDUCTION MOTOR SHOWING THE EFFECT OF VARYING THE RESISTANCE OF THE ROTOR WINDING.



CURVE

rotor pole must be sufficient to accelerate the rotor from the 95% speed to synchronous speed in one (1) revolution. If the slip is too great, (the speed too low) at the time field current is applied in an attempt to synchronize, the rotor will slip poles, the speed will decrease and the starting attempt must be discontinued before the rotor overheats. To have high starting torque, the damper or cage winding should have high resistance and the maximum speed as an induction motor may be well below 95% of synchronous speed, so that the machine cannot be synchronized. To obtain the combination of high starting torque and low slip, a double cage winding can be used in larger machines. The high slip frequency at standstill and the high reactance of the combination cage winding forces the rotor current into the top winding which has high resistance. At lower slip frequencies, the rotor current flows in the bottom cage winding also and the winding then has low resistance. This double cage winding was invented and first used by Dolivo Dobrowolsky in 1889.

Solid-Rotor Machines

If a synchronous machine has a solid pole face, a damper circuit is difficult to install and its effect is not pronounced. The characteristics of a solid-pole, Lundell generator starting at no-load, rated voltage, are shown on Curve 3.

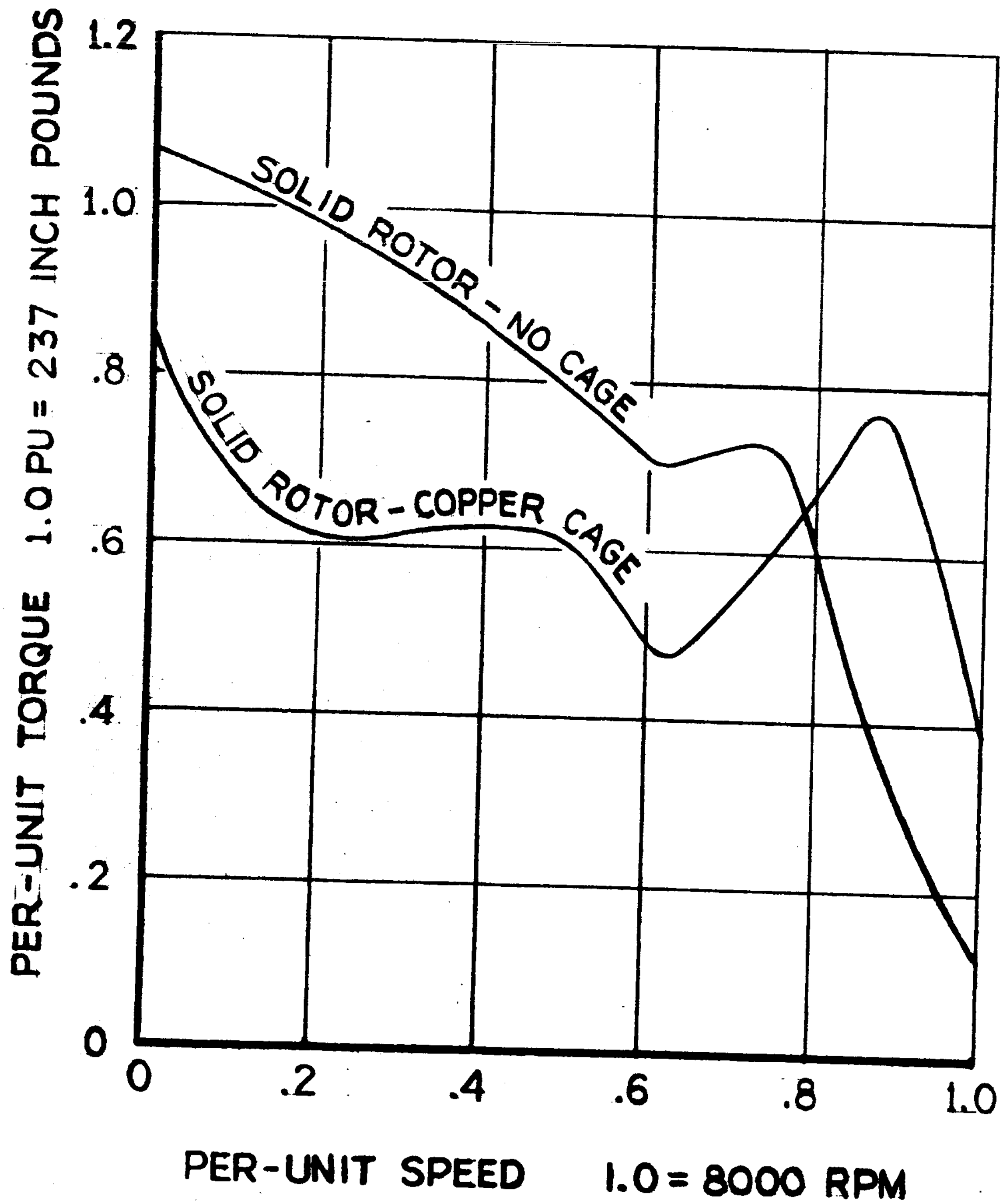
The starting characteristics of the solid rotor are shown with and without a copper cage winding. Both rotors pulled into synchronism quickly (i.e., without hesitation or any evidence of marginal operation) without field excitation. The test curves show that the copper cage does increase torque near synchronism.

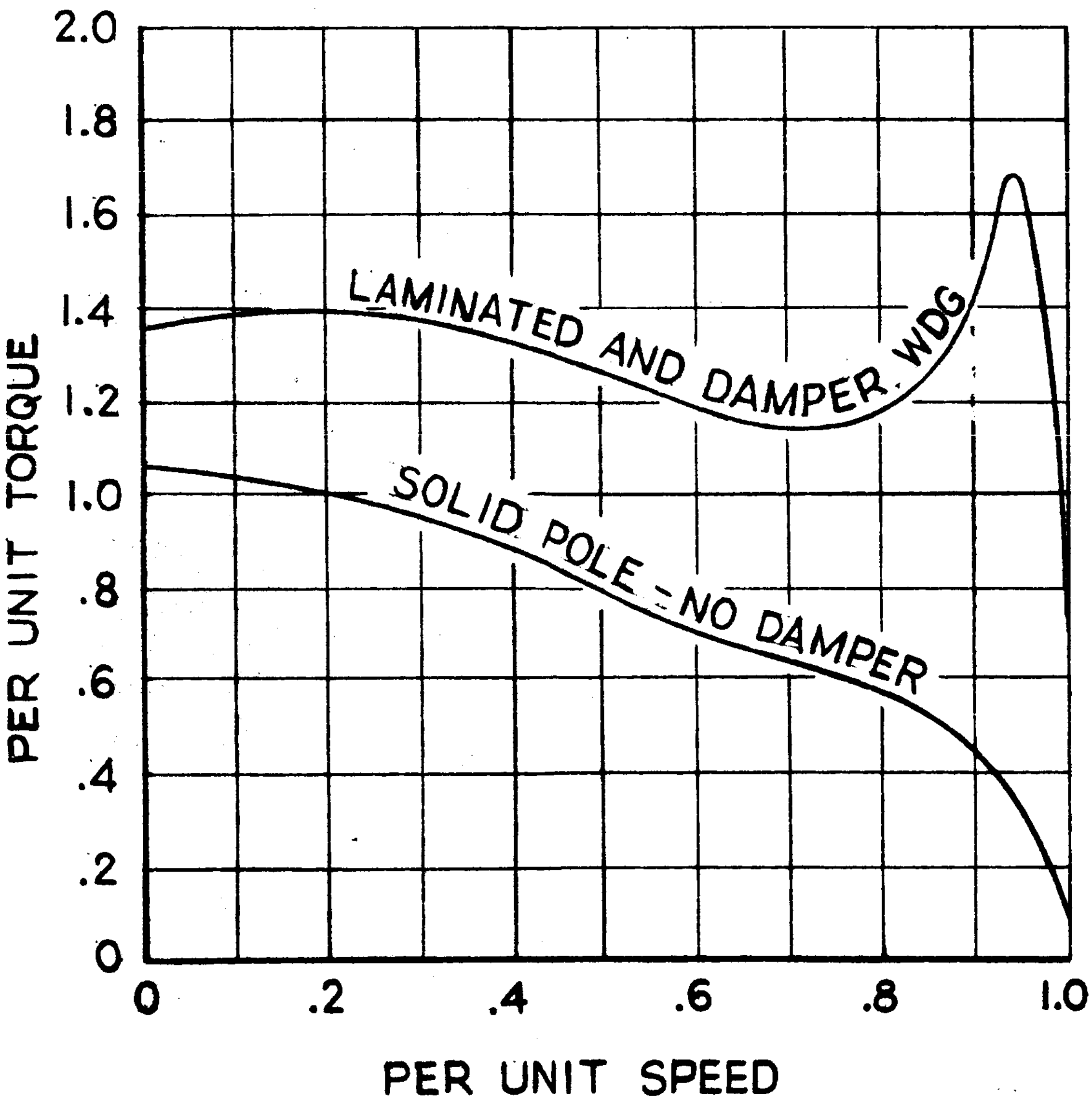
The solid rotor synchronous motor is usually impossible to synchronize under load and some designs cannot be relied upon to synchronize at no load unless special steps are taken. Such special steps may be operating at a frequency higher than rated during the start so that the terminal speed of the rotor is above rated synchronous speed, then reducing the frequency of the supply current faster than the rotor speed can drop. The rotor will then easily synchronize with the supply.

SPEED-TORQUE CHARACTERISTIC OF A TWO-COIL LUNDELL GENERATOR WITH SOLID POLE FACES.

TWO ROTORS WERE TESTED -- ONE WITH COPPER CAGE AND ONE WITHOUT.

GENERATOR RATING 30 KVA, .75 PF, 400 CPS, 8000 RPM.





Comparison of speed torque characteristics to be expected from conventional salient-pole generators with damper windings and solid-pole Lundell generators without damper windings (X_d = 160% approx.).

Another procedure that can sometimes be resorted to is to use a small induction motor having a higher synchronous speed and mounted on the same shaft as the large machine. The small machine will assist the large machine enough to drive it up to synchronous speed. Starting motors are sometimes used on large synchronous condensers where normal starting currents in the large machine would cause a severe voltage dip on the utility distribution system.

Some of the brushless generators have rotors that can easily be laminated and some do not. If the rotor speed is not too great, the homopolar inductor generator can have laminated rotors and also cage windings. The Lundell generators are difficult to make with laminated rotor poles. The heteropolar inductor cannot have a cage winding at all and we do not know how to use it as a motor. The cascade machine has its cage winding on the rotor for motor operation and on the d-c poles for generator operation.

Of the synchronous generators, the solid rotor machines can operate longest as induction motors. The losses in the solid rotor are not concentrated in small bars but are distributed well over the entire rotor surface. The heat transfer is fast and the entire rotor stores the heat. The laminated rotor with a small cage winding has its losses concentrated in the bars and heat transfer from the bars to the steel laminations is poor.

Continuous Operation

When some significant load is to be carried by a synchronous machine for any appreciable time such as 20 HP motor load on a 20 KVA generator, the machine must be in synchronism - both to carry the load and to survive for more than a few minutes (of the order of 5 minutes).

If the load and speed are both reduced enough, the generator can operate continuously as an induction motor because the rotor has some continuous load capability as an induction motor.

Rotating Rectifier Machine

The wound-pole synchronous generators with rotating rectifiers on or in the shaft have a special starting problem that usually prevents their being considered for motor duty.

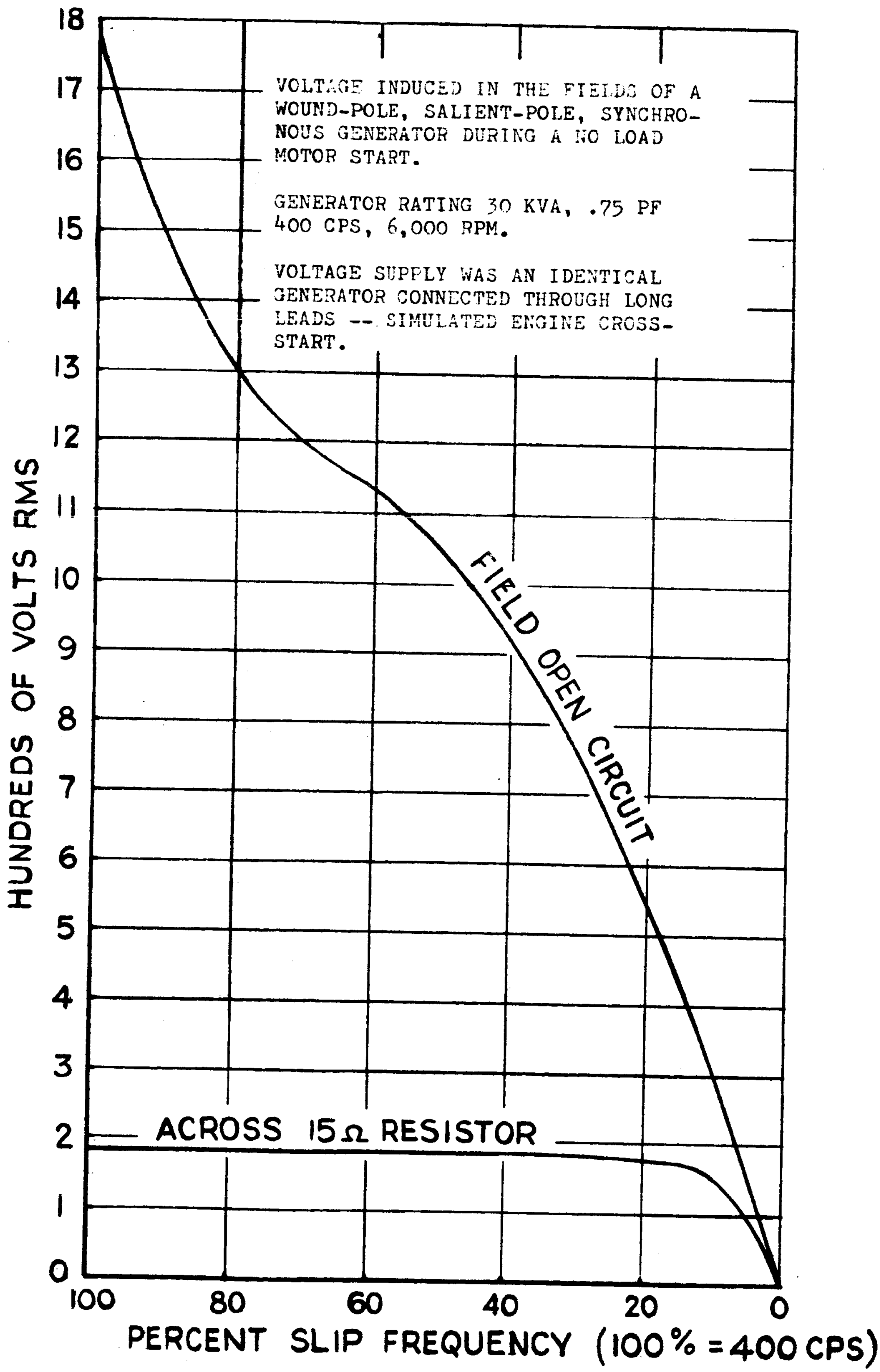
When a wound-pole synchronous machine is started as a motor, the fields are shorted through a starting resistance that can be zero or some finite value. If the fields are open, the induced voltage in the field is dangerous to the field insulation. Curve 4 shows the field voltage of a 30 KVA, 6000 rpm wound-pole synchronous generator during a motor start. The fields were open circuited during one start and shorted through a 15 ohm resistor during another start. The resulting curves demonstrate that the maximum current induced was 12-1/2 amperes and that the induced voltage on open circuit was 1800 volts RMS at standstill and 300 volts RMS at 90% speed.

When rectifiers are used in the excitation supply circuit, they block on one half cycle so that the resistance presented by them is, for practical purposes, infinite. Since obtainable rectifiers cannot withstand 2000 (+) volts or even 650 (+) volts in the reverse direction, the fields must still be shorted during the start cycle and then energized to pull the machine into synchronism.

To short the fields during the start, three methods that have been tried are:

1. Short the fields by using slip rings, brushes, and a relay. Open the relay at end of induction motor start.
2. Use a centrifugal switch that shorts the fields at standstill and opens them at 90% or more or synchronous speed.
3. Use controlled diodes with the rectifier bridge and apply them in such a way that they short the motor field automatically during the start cycle.

Stationary coil, brushless machines do not have a comparable starting problem.


VOLTAGE INDUCED IN THE FIELDS OF A WOUND-POLE, SALIENT-POLE, SYNCHRONOUS GENERATOR DURING A NO LOAD MOTOR START.
GENERATOR RATING 30 KVA, .75 PF 400 CPS, 6,000 RPM.
VOLTAGE SUPPLY WAS AN IDENTICAL GENERATOR CONNECTED THROUGH LONG LEADS -- SIMULATED ENGINE CROSS-START.
FIELD OPEN CIRCUIT
ACROSS 15Ω RESISTOR
HUNDREDS OF VOLTS RMS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
100
80
60
40
20
0
PERCENT SLIP FREQUENCY (100% = 400 CPS)

THE PHYSICAL DIMENSIONS OF LUNDELL-TYPE GENERATORS

IN BRIEF

For a given Lundell generator type having a given rotor diameter there is an optimum stator length and if the stator is made longer than the optimum length, the output of the machine will decrease.

The useful flux of any Lundell generator must pass through the rotor shaft. The flux-carrying capability of the shaft limits the maximum output obtainable from any given rotor diameter.

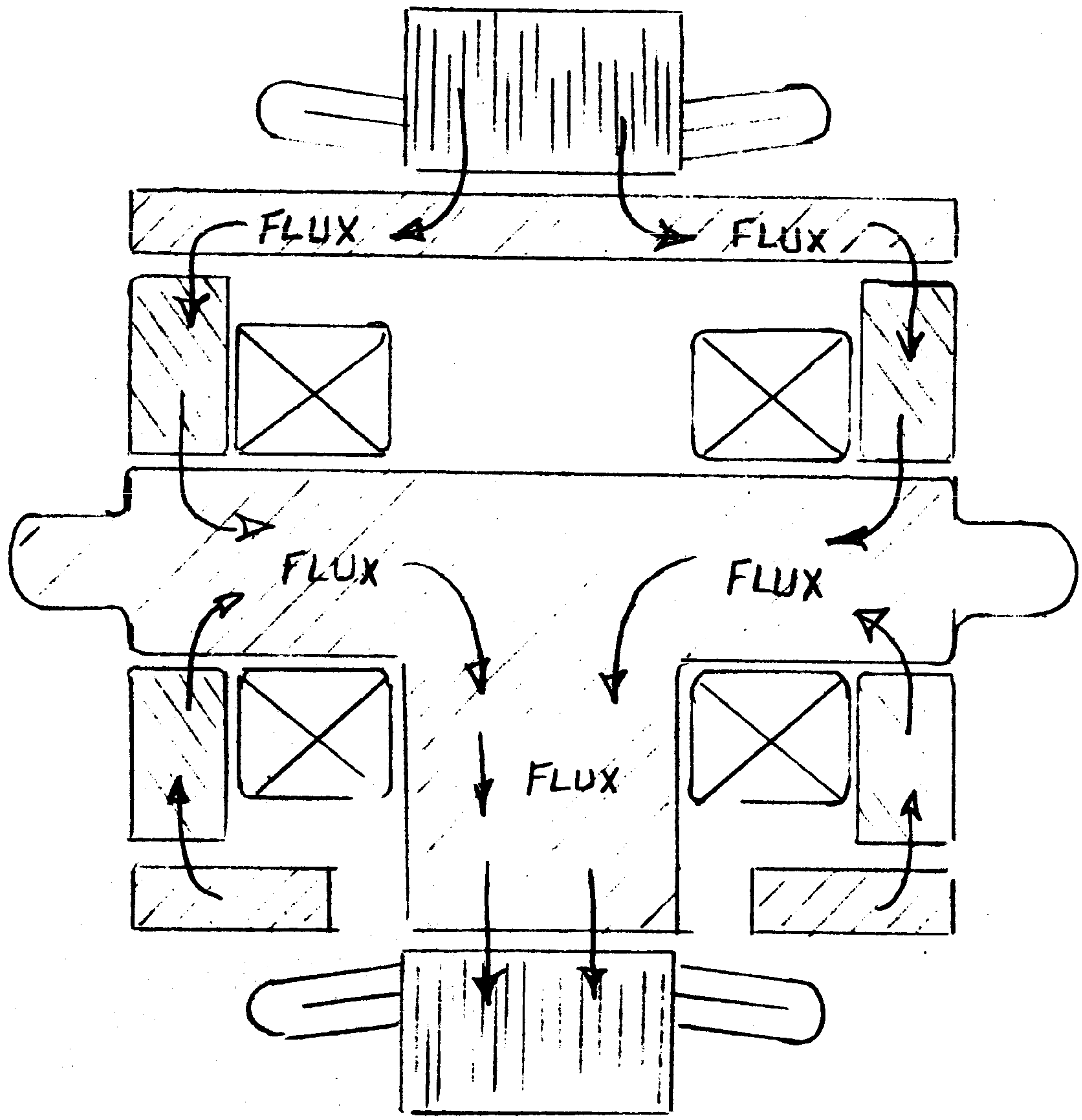
DISCUSSION

There are two arbitrary types of Lundell radial-gap generators. One type has a coil and magnetic shaft between the two sets of poles and the flux circuit is completed through the shaft into one set of poles, into the stator and out again into the other set of poles and back into the shaft section between the pole carrying flux plates. This is the type of generator used for automotive service and an adaptation of this type has a parasitic air-gap allowing it to be brushless. This general type of Lundell generator cannot practically have a shaft cross section of more than 20% of the stator bore cross section area, because of the area taken up by the poles themselves and the exciting coils.

The Lundell generators that have their flux circuits completed outboard of the pole structures can have larger magnetic sections bringing the pole flux into the pole pieces. Two of these generators are the two-coil Becky-Robinson machine and the German Lundell which completes its flux circuit in a yoke outside of the stator.

TWO-COIL LUNDELL (BECKY-ROBINSON)

In the Becky-Robinson Lundell generator, the combined shaft and rotor skirt area that can be allowed for carrying flux in or out of the rotor is approximately



FLUX CIRCUIT OF A TWO-COIL LUNDELL
OR BECKY-ROBINSON GENERATOR

30% of the total cross section area of the stator bore. This value can be considered a maximum because of the area that must be left for excitation coils.

At $Bg = 40\ Kl/in.^2$

and Leakage flux = 40% of total rotor flux

Pole embrace = .5 and Cp = .5

The total shaft flux entering the rotor from the two ends combined is equal to the flux in the shaft on one end plus the flux in the skirt on one end.

Shaft flux at 100 kl/in^2 density $= \frac{.3\pi d^2}{4}(100)$

Total useful flux reaching stator $= \frac{.3\pi d^2}{4}(100).6$

Hypothetical total air gap flux at 40 Kl/in^2 gap density $= \pi dl\ (40)$

Hypothetical total air gap flux $= \frac{.3\pi d^2}{4} \cdot \frac{60.0}{Cp}$

$$= \frac{.3\pi d^2 60}{4(.5)} = 9\pi d^2$$

$$\pi d\ell(40) = 9\pi(d)^2$$

$$\ell = \frac{9}{40}d = .225d$$

On this basis, the KVA output of a two-coil Lundell generator of the Becky-Robinson type =

$$KVA = \frac{Bg\ d^2 1\ (RPM)\ A}{90 \times 10^7} = \frac{40\ (.225d^3)\ RPM\ A}{90 \times 10^7}$$

If A = 900 is accepted as a maximum load on the stator -

$$KVA = \frac{40\ (.225d^3)\ RPM}{10^6} = \frac{9d^3\ RPM}{10^6}$$

OUTPUT VS ROTOR DIAMETER FOR A TWO-COIL LUNDELL GENERATOR OF BECKY-ROBINSON TYPE

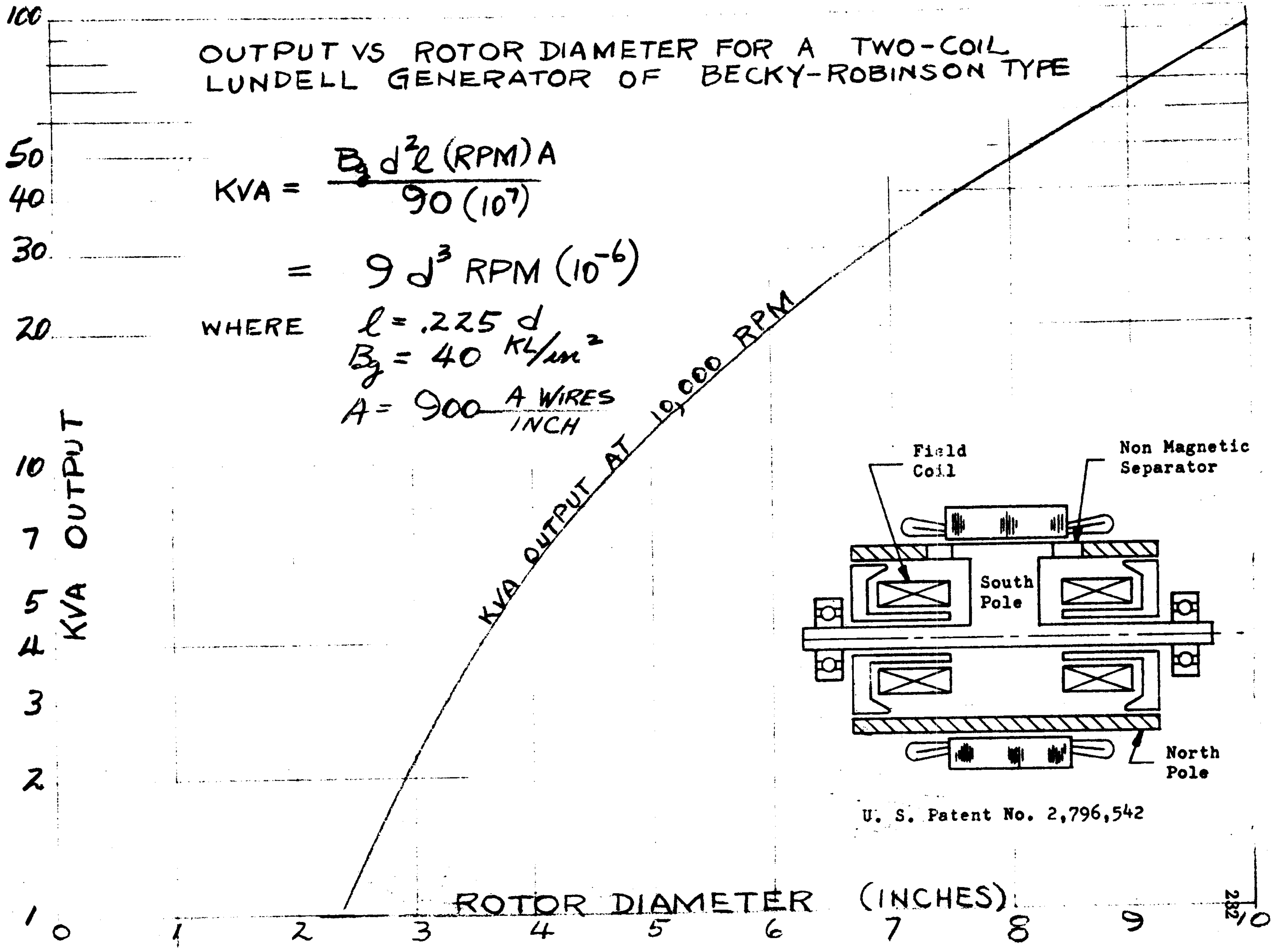
$$KVA = \frac{B_g d^2 \ell (RPM) A}{90(10^7)}$$

$$= 9 d^3 RPM (10^{-6})$$

WHERE $\ell = .225\ d$

$B_g = 40\ KL/in^2$

$A = 900 \frac{A\ WIRES}{INCH}$

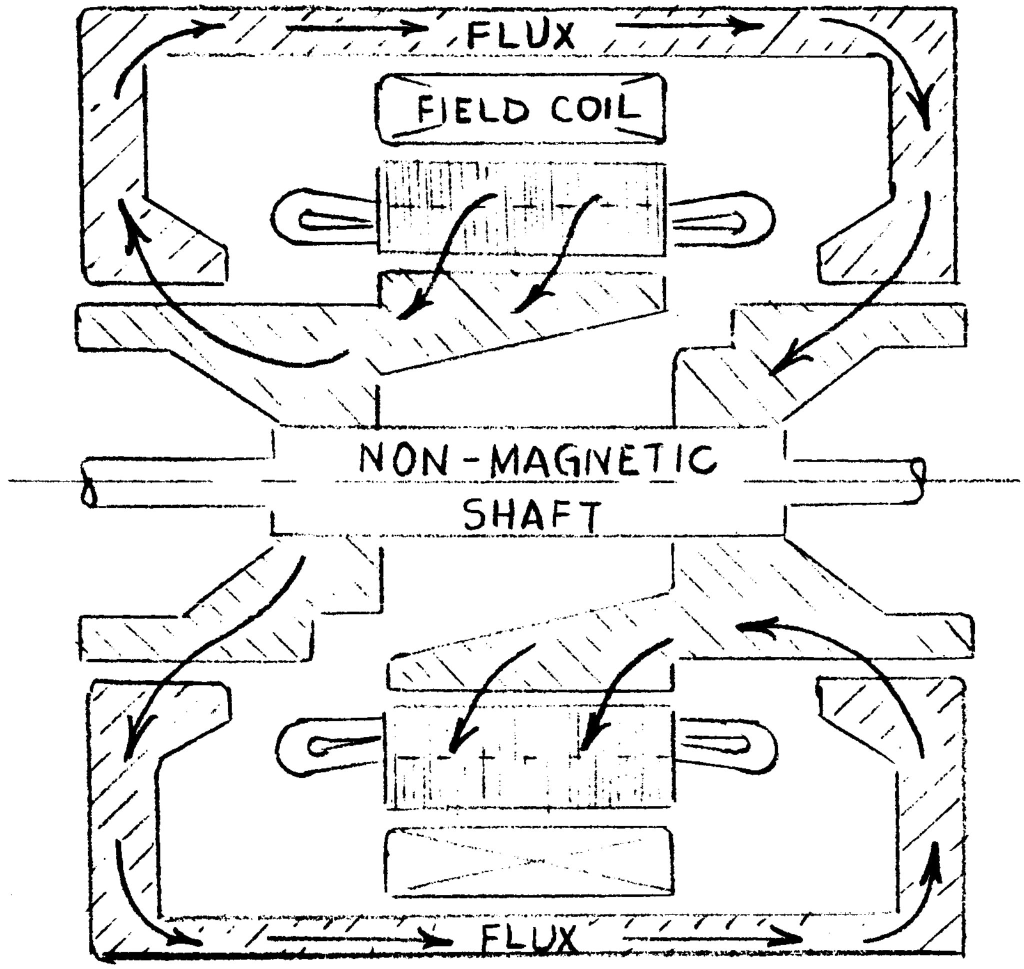


and, $d = \sqrt[3]{\frac{KVA\ (10^6)}{9\ (RPM)}}$

d	d^3	$\frac{9\ d^3\ RPM}{10^6}$	KVA at 10,000 RPM
3	27	$207\ \frac{RPM}{10^6}$	2.07
4	64	$576\ \frac{RPM}{10^6}$	5.76
5	125	$1125\ \frac{RPM}{10^6}$	11.25
6	216	$1944\ \frac{RPM}{10^6}$	19.44
7	343	$3087\ \frac{RPM}{10^6}$	30.87
8	512	$4608\ \frac{RPM}{10^6}$	46.08
9	729	$6561\ \frac{N}{10^6}$	65.61
10	10^3	$9000\ \frac{N}{10^6}$	90

OUTSIDE-COIL LUNDELL

The Lundell generator having the coil or coils in the housing or yoke can be made with slightly larger pole areas than those of the two coil Becky-Robinson Lundells. In some cases, the total pole base area could be .4 of the bore cross-section area or $.4\ \frac{\pi d^2}{4}$ (100) at 100 kl/in^2 density in the iron. If the leakage can be held to .4 of the flux entering the pole, the useful flux crossing



FLUX CIRCUIT OF AN OUTSIDE-COIL LUNDELL GENERATOR the air gap will be =

$$\phi p \text{ across gap} = .4 \frac{\pi d^2}{4} (.6)(100) = 6\pi d^2$$

The hypothetical total flux in the air gap = $\phi_T = \frac{\phi P}{Cp} = \frac{6\pi d^2}{.5} = 12\pi d^2$

ϕ_T also = $\pi d1$ (40) for 40 Kl/in^2 gap density.

$$\pi dl\ (40) = 12\pi d^2$$

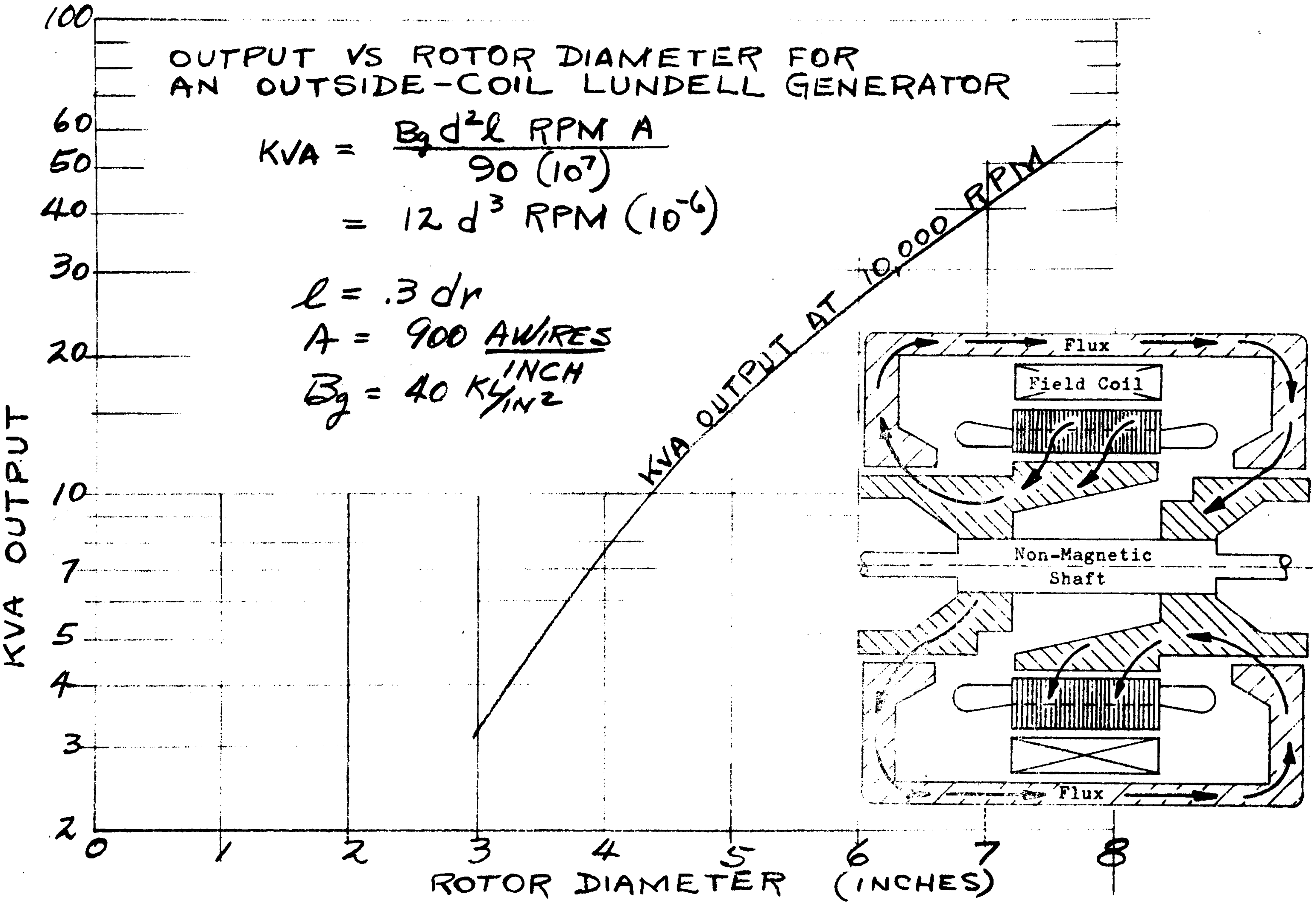
$$\ell = \frac{12d^2\pi}{\pi d(40)} = \frac{12\ d}{40} = .3d$$

$$KVA = \frac{Bg\ A\ d^2 1\ RPM}{90 \times 10^7}$$

If the ampere loading is 900 ampere wires/inch and speed is 10,000 rpm

$$KVA = \frac{40\ (900)\ .3d^3\ (10^4)}{90 \times 10^7} = .12d^3$$

d	$.12d^3$	= KVA at 10,000 RPM
3	3.24	3.24
4	7.68	7.68
5	15	15
6	25.9	25.9
7	41.2	41.2
8	61.4	61.4


OUTPUT VS ROTOR DIAMETER FOR
AN OUTSIDE-COIL LUNDELL GENERATOR
$KVA = \frac{B_g d^2 \ell \; RPM \; A}{90 (10^7)}$
$= 12 d^3 \; RPM \; (10^{-6})$
$\ell = .3 \, dr$
$A = 900 \; \frac{A \; WIRES}{INCH}$
$B_g = 40 \; K \frac{L}{IN^2}$
KVA OUTPUT AT 10,000 RPM
Flux
Field Coil
Non-Magnetic
Shaft
Flux
KVA OUTPUT
100
60
50
40
30
20
10
7
5
4
3
2
0
1
2
3
4
5
6
7
8
ROTOR DIAMETER (INCHES)

AXIAL AIR GAP LUNDELL GENERATORS

Axial air gap synchronous generators have definite design limits that allow the prediction of generator output from stator O.D. and RPM.

Discussion

When the axial air gap machine is worked to definite limits of current loading and air gap density, simply specifying the speed and the KVA output determines the diameter of the stator.

To determine the size of a specific type of generator at different speeds and ratings, a stator current loading limit and an air gap density limit should be assumed. For the determination of the size of the axial gap generators, an ampere loading of 900 ampere-conductors per inch of circumference of the stator has been used. This circumference is at the average diameter = $\frac{OD + ID}{2}$. The gap density has been fixed at 40 Kl/in^2. This density is the actual maximum of the flux wave under each pole. The equations used assume a sine wave of flux, or that the maximum fundamental of the pole flux wave is equal to the actual maximum of the flux wave. For concentric poles (square flux waves), this occurs at a pole embrace of 55%.

40 Kl/in^2 gap density and 900 amp-conductors per inch are set as the design limits.

The following discussion explains the derivation of the output equation used to determine generator sizes.

The output of a three phase generator is $KVA = \frac{I_{LL}\, E_{LL}\, \sqrt{3}}{10^3}$

The voltage is defined by -

$$E_{LL} = \frac{\phi_T\,(RPM)\,Cw\,Ne}{60 \times 10^5}$$

See derivation elsewhere in report.

Where ϕ_T = Hypothetical total flux in air gap in Kilolines,

$$Cw = \frac{E_{LL}}{M\ Eph} \cdot \frac{C_1 K_d}{\sqrt{2}} = .39\ C_1$$

m = No. of phases

C_1 = Ratio $\frac{\text{maximum fundamental}}{\text{actual maximum}}$ of the flux wave = 1.0 for sine wave

Ne = Total effective conductors in the machine

The basic voltage equation is substituted in the output equation.

$$KVA = E_{LL}\ I_L\ \frac{\sqrt{3}}{10^3} = \frac{\phi_T\ RPM\ C_w\ Ne\ I\ \sqrt{3}}{60 \times 10^5 \times 10^3}$$

$$\phi_T = B_{Gap}\ A_{Gap} \text{ and}$$

$$I = \frac{A\ \pi D}{Ne} \text{ where}$$

A = Ampere wire/inch loading of stator based on the average diameter of stator

$$KVA = \frac{Bg\ (\pi D \ell_c)\ RPM\ (.39\ C_1)\ Ne\ \sqrt{3}}{60 \times 10^8}\ \frac{A\ \pi D}{Ne}$$

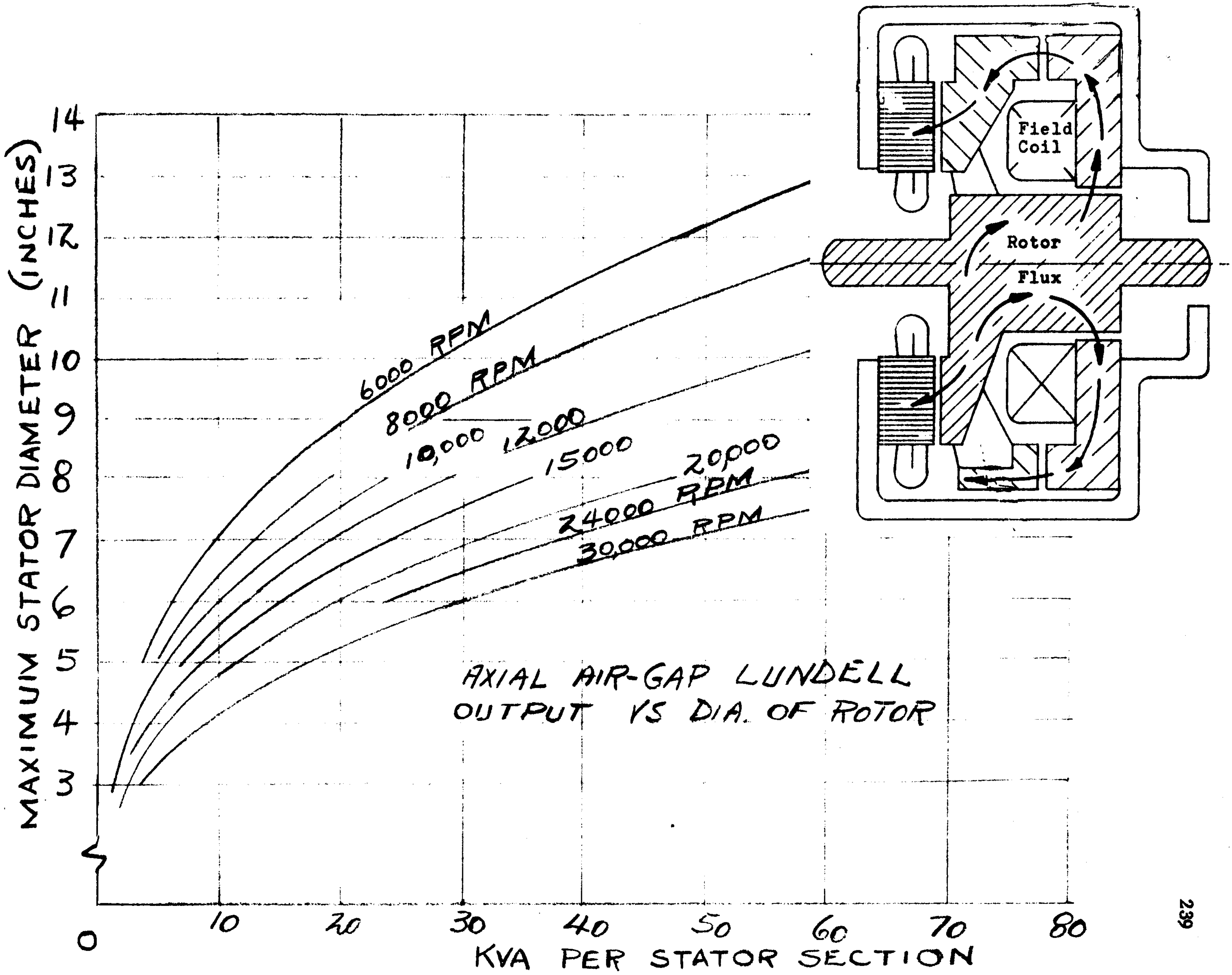
$$KVA = \frac{Bg\ 9.85\ D^2\ \ell_c\ RPM\ .39\ C_1\ A\ \sqrt{3}}{60 \times 10^8}$$

$$KVA = \frac{Bg\ D^2 \ell_c\ RPM\ A}{90 \times 10^7} \quad \text{Basic eqn.}$$

For axial air gap machines

D = average diameter of stator

$$= \frac{OD + ID}{2}$$


Field
Coil
Rotor
Flux
6000 RPM
8000 RPM
10,000
12,000
15000
20000 RPM
24000 RPM
30,000 RPM
AXIAL AIR-GAP LUNDELL
OUTPUT VS DIA. OF ROTOR
MAXIMUM STATOR DIAMETER (INCHES)
KVA PER STATOR SECTION
0
10
20
30
40
50
60
70
80
3
4
5
6
7
8
9
10
11
12
13
14

For radial air gap machines

$$D = \text{rotor diameter.}$$

To allow a general treatment of the axial air gap machine, the typical design will be considered to have the following characteristics:

$$\text{Stator OD} = \frac{3}{2}\ \text{stator ID}$$

$$\text{Gap density} = Bg = 40\ \text{Kl/in}^2$$

$$\text{Ampere loading} = A = 900\ \frac{\text{Amp. Cond.}}{\text{in.}}$$

$$C_1 = \text{Field form factor} = 1.0\ \text{(assume sine wave)}$$

Then,

$$KVA = \frac{Bg\, D^2_{avg}\, \ell c\ RPM\ A}{90 \times 10^7}$$

$$D_{avg} = \frac{OD + \frac{2}{3} OD}{2} = \frac{5}{6}\ OD$$

$$\ell c = \frac{1}{6}\ OD$$

and,

$$KVA = 40\ \frac{25}{36}\ (OD)^2\ \frac{1}{6}\ (OD)\ \frac{RPM\ (900)}{90 \times 10^7},$$

$$KVA = \frac{4.63\ (OD)^3\ RPM}{10^6}$$

$$\text{Area of stator} = .437\ (OD)^2$$

$$\text{Total flux} = 40\ (\text{Area of stator}) = 17.5\ (OD)^2\ \text{Kl.}$$

$$\phi_P = \text{approx.}\ \frac{\phi_T}{\text{Poles}} \times .56$$

$$\phi\ \text{shaft} = \text{approx.}\ \phi_T \times .27$$

When the ID of the stator is fixed at $\frac{2}{3}$ OD, the diameter which divides the stator into two equal areas is .85 OD. The average diameter is $\frac{5}{6}$ OD or .835 OD -- a 1.75% difference. This difference will be ignored and the average diameter, $\frac{5}{6}$ OD will be used as the design diameter for all calculations.

For axial air gap generators

$$KVA = \frac{4.63}{10^6} (OD)^3 \text{ RPM}$$

OD	$(OD)^3$	$\times \frac{4.63}{10^6}$	x 6000	12000
3	27	$.125\ (10^{-3})$	.75	1.5
4	64	$.296\ (10^{-3})$	1.77	3.54
5	125	$.58\ (10^{-3})$	3.48	6.96
6	216	$1.00\ (10^{-3})$	6.00	12.0
7	343	$1.59\ (10^{-3})$	9.55	19.1
8	512	$2.37\ (10^{-3})$	14.2	28.4
9	730	$3.38\ (10^{-3})$	20.3	40.6
10	10^3	$4.63\ (10^{-3})$	27.7	55.4
11	1330	$6.16\ (10^{-3})$	37.0	74.0
12	1728	$8.0\ (10^{-3})$	48.0	96.0
13	2197	$10.15\ (10^{-3})$	61.0	122.0
14	2744	$12.7\ (10^{-3})$	76.3	152.6

KVA for RPM Shown

OD	6000	8000	10,000	12,000	15,000	20,000	24,000
3	.75	1.0	1.25	1.5	1.88	2.5	3.0
4	1.77	2.36	2.95	3.54	4.42	5.9	7.08
5	3.48	4.63	5.8	6.96	8.7	11.6	13.92
6	6.00	8.0	10.0	12.0	15.0	20.0	24.0
7	9.55	12.7	15.9	19.1	23.9	31.8	38.2
8	14.2	18.9	23.6	28.4	35.5	47.2	56.8
9	20.3	27.1	33.8	40.6	50.7	67.6	81.2
10	27.7	36.9	46.2	55.4	69.2	92.4	110.8
11	37.0	49.3	61.7	74.0	92.5	123.4	148.0
12	48.0	64.0	80.0	96.0	120.0	160.0	192.0
13	61.0	81.3	102.0	122.0	153.0	204.0	244.0
14	76.3	101.5	127.0	152.6	191.0	254.0	305.2

ESTIMATING THE COIL WEIGHT AND I^2R LOSS

Based on 80% ratio of $\frac{\text{Field Copper Area}}{\text{Total Coil Area}}$ for field coils and a current density of 5000 amps/in^2, 4000 ampere turns would require one square inch of coil cross section.

Assume a square copper coil in all cases then using the coil inner diameter; d_c:

$$WT = \left[d_c + \frac{AT}{4000} \times \frac{AT}{4000}\right] .321 \text{ lbs.} \qquad (1)$$

Where d_c = coil inner dia, inches

Here the weight of coil hangers and insl. is estimated at 20% of the total.

$$\frac{I^2R\ \text{Loss}}{\text{Lb. Cu.}} = \left(\frac{\text{Amps}}{\text{In.}^2}\right)^2 \frac{\rho}{\#/\text{in}^3} = 25\,\frac{(10^6)}{.321}\,\rho(.8)$$

Where ρ = Coil resistivity in microhm inches

at 400°F and 5000 amps/in^2 in CU, use Wt. obtained in equation (1) x .8

$$I^2R\ \text{Loss} = \frac{25\ (1.17)}{.321}\ .8\ \underset{\text{Gross}}{(\text{WT Coil})} = 73\ (\text{WT.})\ \text{Watts} \quad (2)$$

@ 400°F (240°C)

ROTOR STRESSES

The speed and rating obtainable from a generator are functions of allowable rotor stresses.

The brushless generator rotors can be made into composite cylinders and preliminary stress treatment can be on the basis of a cylinder of homogeneous material.

Maximum stress in a homogeneous solid disk is -

$$\text{Max. } S_r = \text{MAX. } S_t = \frac{1}{8}\,\frac{\gamma W^2}{386.4}\,(3 + v)\ R^2$$

R = disk outside radius, inches ; ω = RAD/SEC

v = Poisson's Ratio = .26 for steel (general approximation)

γ = density LB/in^3 = .283 for steel ; N = REV/MIN

$$S = \frac{.283}{8}\,\frac{(2\pi)^2 N^2}{386.4\ (3600)}\,(3.26)\ R^2 \qquad ;\ S = \text{PSI}$$

$$= \frac{3.26}{10^6}\,N^2 R^2$$

A more realistic condition usually is represented by a cylinder with a hole in the center.

The maximum stress in a homogeneous circular disk or a cylinder with a small hole in the center is:

$$\text{Max } S_t = \frac{1}{4} \frac{\gamma W^2}{386.4} \left[(3 + v) R^2 + (1 - v) R_o^{\,2} \right]$$

R = disk outside radius, inches

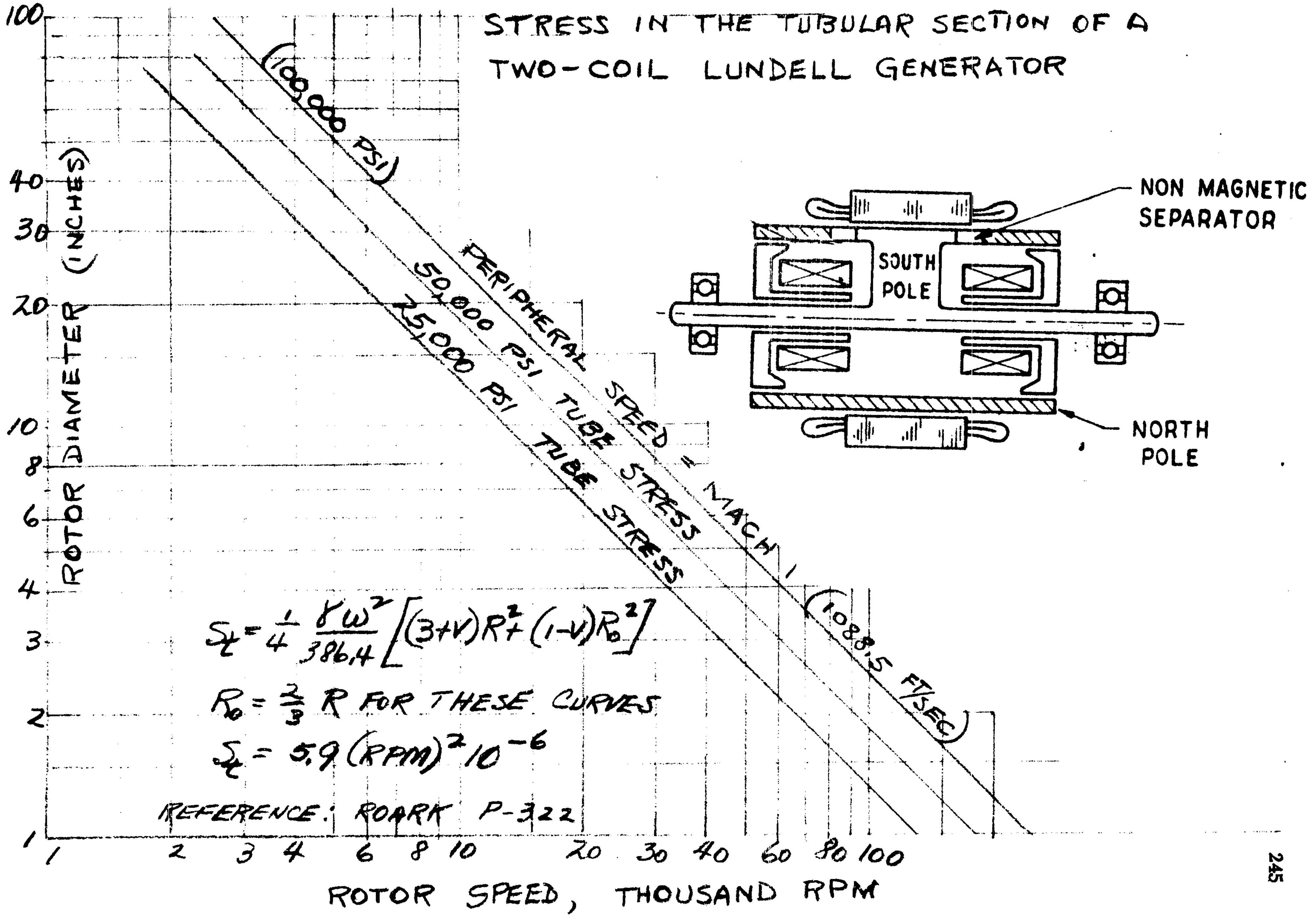
R_o = disk inside radius, inches

If R_o is small and insignificant

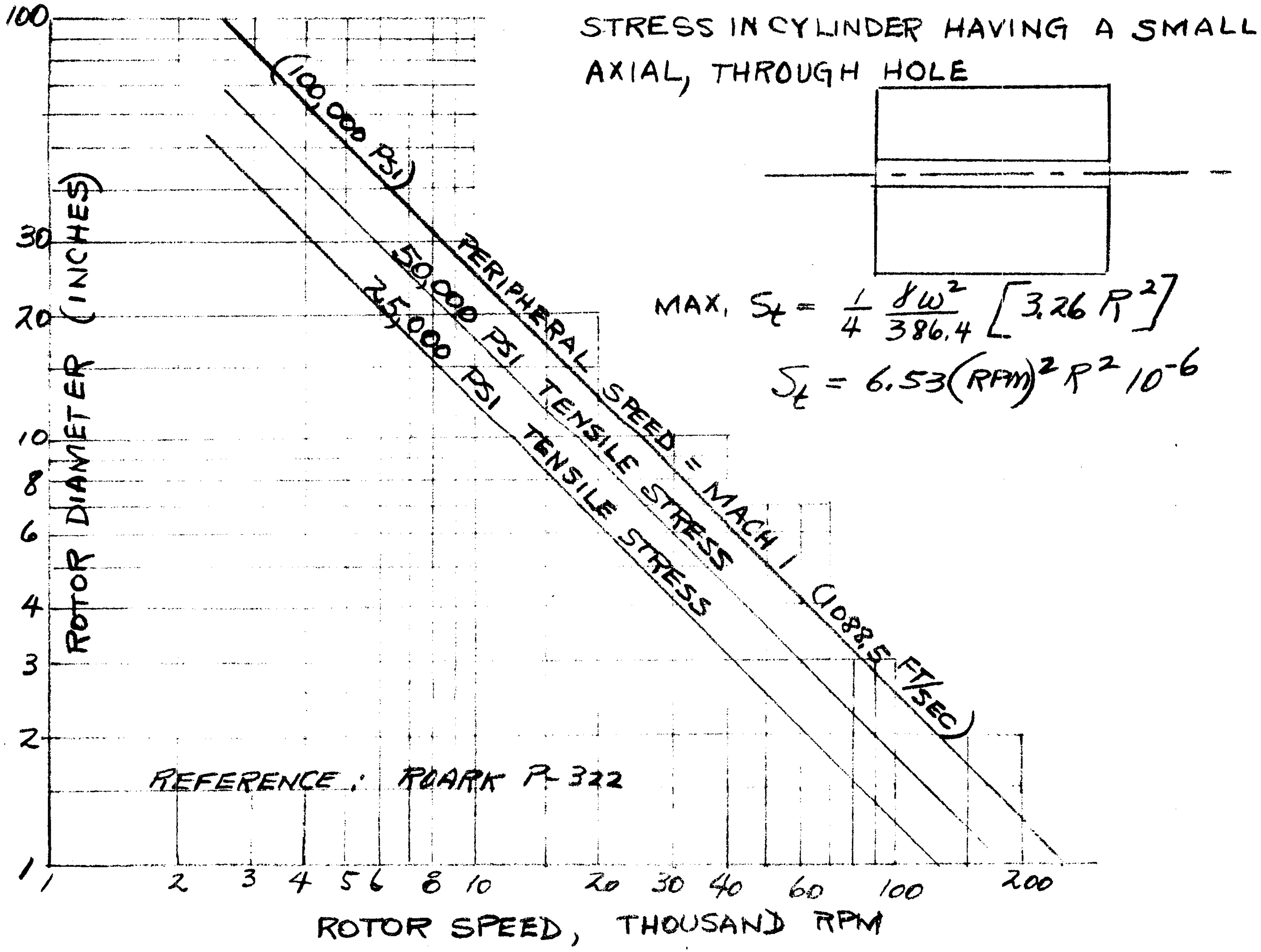
$$\text{Max } S_t = \frac{1}{4} \frac{\gamma W^2}{386.4} (3 + v) R^2 \quad \text{PSI}$$

This equation gives twice the stress calculated in a disk without a hole or -

$$S_t = \frac{6.52}{10^6} N^2 R^2$$



STRESS IN THE TUBULAR SECTION OF A TWO-COIL LUNDELL GENERATOR
NON MAGNETIC SEPARATOR
SOUTH POLE
NORTH POLE
(100,000 PSI)
PERIPHERAL SPEED = MACH 1 (1088.5 FT/SEC)
50,000 PSI TUBE STRESS
25,000 PSI TUBE STRESS
$S_t = \frac{1}{4}\frac{\gamma\omega^2}{386.4}\left[(3+\nu)R^2 + (1-\nu)R_0^2\right]$
$R_0 = \frac{2}{3}R$ FOR THESE CURVES
$S_t = 5.9\,(RPM)^2\,10^{-6}$
REFERENCE: ROARK P-322
ROTOR DIAMETER (INCHES)
100
40
30
20
10
8
6
4
3
2
1
1
2
3
4
6
8
10
20
30
40
60
80
100
ROTOR SPEED, THOUSAND RPM


STRESS IN CYLINDER HAVING A SMALL, AXIAL, THROUGH HOLE
MAX. $S_t = \frac{1}{4} \frac{\gamma \omega^2}{386.4} \left[3.26 R^2 \right]$
$S_t = 6.53 (RPM)^2 R^2 10^{-6}$
(100,000 PSI) PERIPHERAL SPEED = MACH 1 (1088.5 FT/SEC)
50,000 PSI TENSILE STRESS
25,000 PSI TENSILE STRESS
REFERENCE: ROARK P-322
ROTOR DIAMETER (INCHES)
ROTOR SPEED, THOUSAND RPM
100
30
20
10
8
6
4
3
2
1
1
2
3
4
5
6
8
10
20
30
40
60
100
200